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A Jurassic Basin: The Glasenbach Gorge, Salzburg, Austria

By DANIEL BERNOULLI & HUGH C. JENKYNS *

With 2 Figures and 6 Plates

Contents

Abstract

The Glasenbach Gorge (Salzburg, Austria) exposes a thick (greater than 300 m) sequence of Jurassic pelagic sediments which can be divided into a basal grey Hornstein- and Fleckenkalk unit (Lower Liassic), a Red Nodular Limestone and Marl unit (Marly Ammonitico Rosso, Middle Liassic to Middle Jurassic) and a Radiolarite unit (Upper Jurassic). Within the lower units, slump folded complexes, pebbly mudstones and turbidites, the latter themselves sometimes involved in slumps, are widespread. The presence of these sedimentary features shows that we are dealing with a primary morphological basin, which we would thus contrast with the Adnet-type swells where condensed calcareous sequences, with ferromanganese crusts and nodules ("seamount facies"), occur.

Within the resediments of the Glasenbach section an evolutionary pattern may be discerned which must reflect the palaeogeographic evolution, presumably a sinking, of the seamount source areas. The first resediments occurring in the Fleckenkalk, are white intraclastic crinoid-echinoid biosparites; within the Red

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*) Present Address: D. BERNOULLI, Geological Institute of the University, Basel, Switzerland, H. C. JENKYNS, Department of Geology, University of Oxford, Great Britain.

Nodular Limestones and Marls pink and red crinoidal and crinoid-pelagic lamellibranch turbidites are present — and these must reflect increasing pelagic influence with accompanying haematitic mineralisation at the source area. Finally towards the top of the Red Nodular Limestones and Marls only intercalations of graded pelagic lamellibranch limestones with little crinoid material can be found. Above this, reflecting basin starvation and probable elimination of local topography, turbidite-free radiolarites appear.

The origin of the "autochthonous" lime mud throughout much of the sedimentary series may be sought in the nanno-organism *Schizosphaerella,* which may occur in rock-forming quantities: coccoliths become more important from the upper Liassic upward.

We estimate depths in the order of hundreds of meters for the Liassic of the Glasenbach Basin, whereas the Adnet Seamounts with their evidence of possible photic conditions, may, during their early history, have lain only some tens or at most some hundreds of metres below the surface.

Zusammenfassung

In der Glasenbach-Schlucht (Salzburg, Österreich) sind mehr als 300 Meter pelagischer Jura-Sedimente aufgeschlossen. Die Serie kann in eine basale Hornstein- und Fleckenkalk-Einheit, eine Einheit roter, zuweilen beiger und grauer, meist knolliger Kalke und Mergel, und eine Einheit von ober-jurassischen Radiolariten unterteilt werden. Resedimentation von Faunen erschwert eine chronostratigraphische Zuordnung, doch dürften die Hornstein- und Fleckenkalke im großen ganzen dem unteren Lias, die roten, knolligen Kalke und Mergel dem mittleren Lias bis Dogger entsprechen. In diesen beiden lithologischen Einheiten treten zahlreiche durch submarine Gleitfaltung verformte Schichtkomplexe, assoziiert mit „Geröllmergeln“ (pebbly mudstones) und Rutschungskonglomeraten, auf. Turbidite sind oft mit solchen Resedimenten genetisch verknüpft, treten aber auch unabhängig von ihnen auf oder können auch in spätere Rutschungen einbezogen werden. Alle diese Erscheinungen zeigen, daß es sich um Becken-Sedimente handelt, welche sich den kondensierten Schwellen-Sedimenten vom Typus Adnet gegenüberstellen lassen.

Die Resedimente des Glasenbach-Profils lassen eine zeitliche Entwicklung erkennen, welche der paläogeographischen Entwicklung, im besonderen einer Absenkung der Material-liefernden Schwellengebiete entspricht. Die frühesten Resedimente in den Fleckenkalken sind weiße, intraklastische Crinoiden-Echiniden Biosparite. In den roten, knolligen Kalken und Mergeln treten bunte Turbidite mit Crinoiden und pelagischen Lamellibranchiaten auf, welche einen vermehrten pelagischen Einfluß mit haematitischer Mineralisation im Ursprungsgebiet erkennen lassen. Im oberen Teil der Formation endlich findet man Turbidite, welche neben pelagischen Lamellibranchiaten nur spärliche Crinoiden-Fragmente führen. Die in der Glasenbach-Schlucht Turbidit-freien Radiolarite zeigen reduzierte Karbonat-Sedimentation und nur geringes submarines Relief (außerhalb der gleichzeitigen Brekzienschüttungen im Südosten) an. Die „autochthone“ pelagische Kalksedimentation wird während langer Zeit von pelagischen Nanno-Organismen

genährt, insbesondere tritt die Form *Schizosphaerella* in gesteinsbildender Menge auf. Coccolithen werden vom oberen Lias an häufiger.

Für die liasischen Becken-Sedimente lassen sich Meerestiefen von mehreren hundert Metern annehmen, während die Schwellen vom Adneter Typus während ihrer frühen Entwicklung im Bereich der photischen Zone, d. h. in einer Meerestiefe von Zehnern von Metern oder wenig mehr lagen.

Introduction

Recent research on pelagic Jurassic sediments from the Eastern Alps (GARRISON & FISCHER 1969; HUDSON & JENKYNS 1969; JURGAN 1969; WENDT 1969) has concentrated on the more condensed limestones (Adnet Limestone facies), since these often contain rich ammonite faunas, and numerous quarries exist where the stone is exploited for ornamental marble. Palaeogeographic situations reconstructed only from a study of these "Schwellen-Fazies", however, can be somewhat misleading, since coeval basinal deposits also occur (eg. HUCKRIEDE 1959; KOCH, STENGEL-RUTKOWSKI & HOFFMANN 1959; JACOBSHAGEN 1964).

We here describe one such basinal succession from the Glasenbach Gorge, a river-cut valley situated a few kilometres south of Salzburg (Fig. 1) in the same tectonic unit as the type-locality of the Adnet Limestone (Tirolian Nappe, cf. PREY et al. 1969). Despite some faulted repetition, a more or less continuous section of Jurassic rocks may be reconstructed from the exposures available (Figs. 1 and 2). Summary descriptions of parts of the section have been given by FUGGER 1906, DEL-NEGRO 1957, 1958, 1959, VORTISCH 1956, 1963, and, more recently, other aspects of the succession have been touched upon by M. SCHLAGER 1960, 1961, 1966, and HALLAM 1967.

It is our purpose in this paper to outline certain sedimentological aspects of the succession and discuss their palaeogeographic significance. Of some importance is the re-interpretation of certain tilted blocks as products of sediment slumping rather than tectonic movement (cf. VORTISCH 1931, 1934, 1937, 1956, 1963, 1968, DEL-NEGRO 1957—1959).

Comparisons are made with palaeogeographic situations reconstructed for the pelagic Jurassic of the Apennines and other parts of the Tethyan realm.

Stratigraphy and description of "autochthonous" rock types

Hornsteinkalk and Fleckenkalk

The basal Hornsteinkalk (1 A in Figs. 1 and 2) consists of a more or less regular alternation of well-bedded grey marly calcilutites and darker grey marls. Dark replacement chert nodules are irregularly distributed in the limestone beds. Particularly near the base of this unit, the limestone beds are riddled with *Chondrites*, with darker infills in a lighter matrix. This presupposes a primary and/or very early diagenetic sediment differentiation between the lighter, more calcareous, and the darker, more argillaceous, muds (cf. HALLAM 1964).

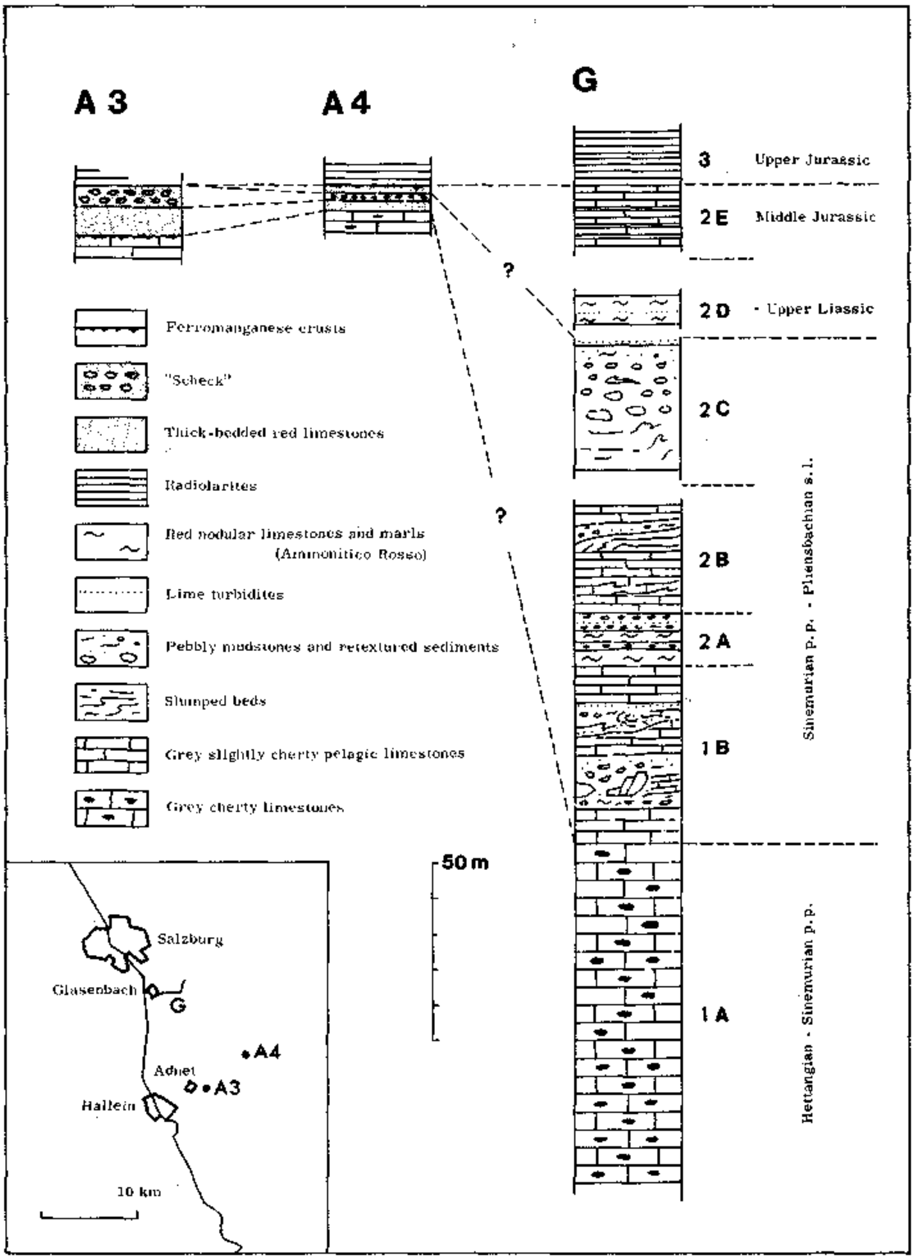

Fig. 1. Index map and columnar sections of Glasenbach basinal sequence (G) and of Adnet "seamount" sequences (A 3, A 4), Salzburg, Austria. Sections A 3 and A 4 from Wendt (1969). Lokationskärtchen und Kolonnenprofile der Serien der Glasenbach-Schlucht (G, Becken) und von Adnet (A 3, A 4; "Seamount"), Salzburg, Österreich. Profile A 3 und A 4 nach Wendt (1969).

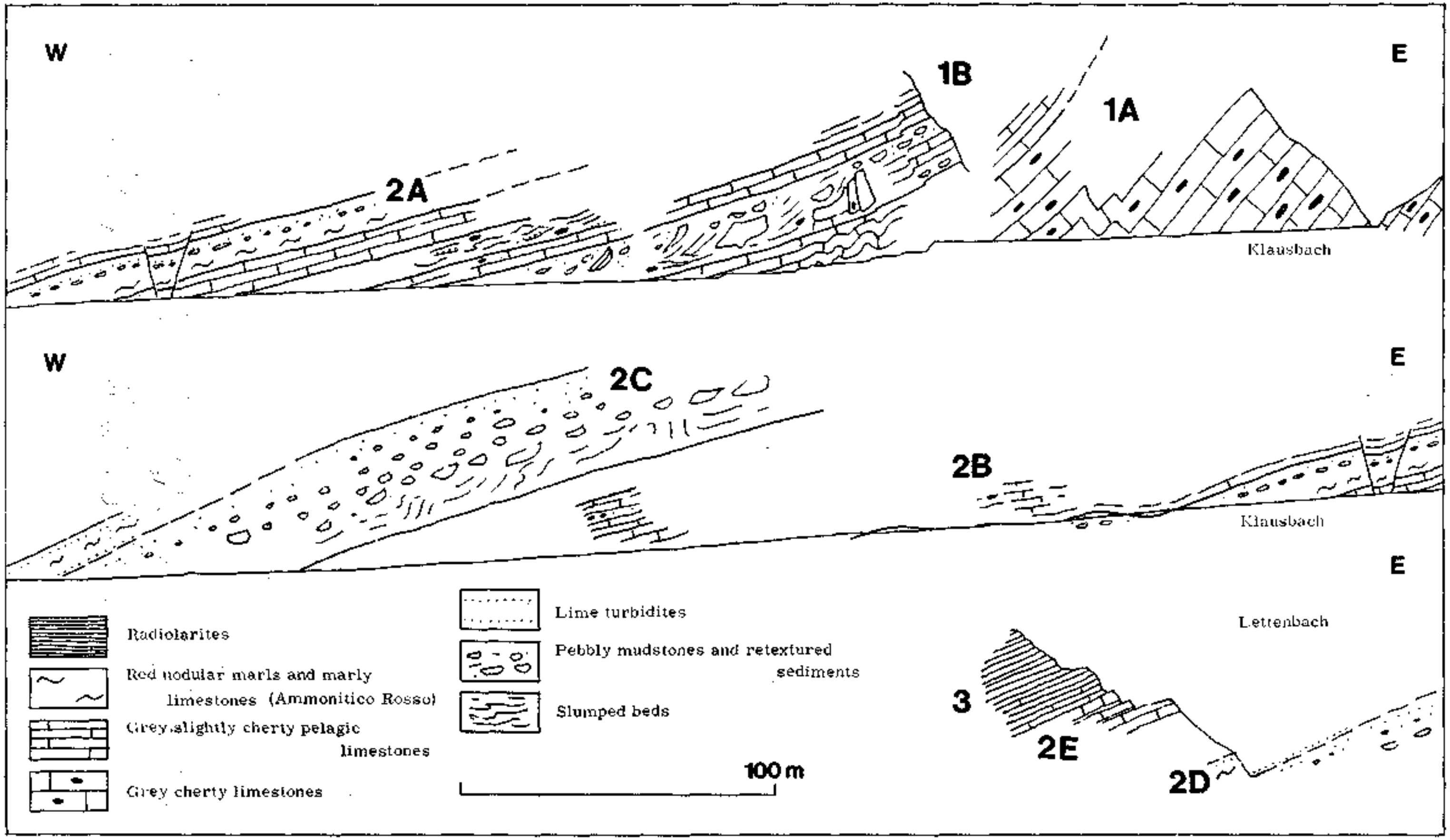

Fig. 2. Schematic sketch of the outcrops in the Glasenbach Gorge, Salzburg, Austria. Projection more or less perpendicular to strike.
Schematische Skizze der Aufschlüsse in der Glasenbach-Schlucht, Salzburg, Österreich. Projektion ungefähr senkrecht zum Streichen.

This lithology contains sponge spicules and radiolaria, which may or may not be carbonate-replaced, set in a micritic or chertified matrix. Ferroan calcite is often involved, sometimes exclusively, in the replacement fabrics; the origin of this iron-rich calcite may be related to the high clay content of this lithology and subsequent diagenesis under reducing conditions (OLDERSHAW & SCOFFIN 1967). Foraminifera occur rarely, as do crinoid fragments.

The Hornsteinkalk passes gradually into a less chert-rich limestone-marl series, here called Fleckenkalk (1 B in Figs. 1 and 2). This also may be extensively burrowed. The microfauna comprises calcite-replaced radiolaria and sponge spicules, with occasional foraminifera, ostracods and crinoids ossicles. The matrix is usually micritic, but may be chertified in places.Ferroan calcite also occurs in replacement fabrics. This unit contains large-scale slump-complexes and lime turbidites (see below). The total exposed thickness for both the Hornsteinkalk and the Fleckenkalk is about 150 metres. The age of both formations encompasses the upper part of the Lower Liassic (FUGGER 1906; DEL-NEGRO 1957; VORTISCH 1963) and possibly part of the Middle Liassic with ammonites of the Hettangian introduced by slumping. The transition of the Fleckenkalk into the overlying Red Nodular Limestones and Marls is relatively sharp.

Red Nodular Limestones and Marls (Marly Ammonitico Rosso)

This unit consists of limestone-marl interbeds or limestone nodules in a marly matrix; the colour of these beds, always more intense in the marls, is usually red, but may vary through cream to pale green. The red nodular limestone contains, in its more calcareous parts, calcite-replaced sponge spicules, crinoid fragments and foraminifera set in a micritic matrix. The more marly ferruginous layers generally have a higher fossil content and are particularly rich in crinoid fragments; in contrast sponge spicules are rare and badly preserved (cf. MIŠÍK 1964; JURGAN 1969).

Slumped beds, pebbly mudstones and associated lime turbidites occur throughout this unit. The most conspicuous slump mass is a "Knollenbreccie" (2 C) some 30 metres thick which can be followed over considerable horizontal distance (PREY et al. 1969; "Hauptknollenbrekzie", VORTISCH 1968).

Above this, pelagic lamellibranchs constitute an important faunal element, whilst sponge spicules become more scarce (2 D). At the top of this unit (2 E) the limestones tend to have a platy aspect with interbedded marls; the beds become progressively more siliceous and grade into the radiolarites above.

The Red Nodular Limestones and Marls have locally yielded rich faunas of ammonites, nautilids, belemnites, with some gastropods and brachiopods. These fossils, however, are mostly badly preserved. Age determinations by FUGGER 1906, DEL-NEGRO 1958, VORTISCH 1956 suggest that the red nodular limestones and marls below the "Knollenbreccie" are essentially Middle Liassic in age.

The "Knollenbreccie" itself contains a rich fauna from which VORTISCH determined ammonites of Hettangian to Carixian age (VORTISCH in DEL-NEGRO 1958), which, if correctly determined, are obviously reworked. During this survey we have identified some Domerian fossils such as *Protogrammoceras* sp., *Arieticeras* sp., and *Glossothyris* (?) *aspasia* (MENEGHINI) (cf. VORTISCH 1956, 1968). The red nodular limestones and marls above this (2 D), most probably comprise the Upper Liassic and the Middle Jurassic. The total thickness of this lithological unit including slump masses is some 140 metres.

Radiolarite

This rock unit consists of a regular alternation of cherts and very thin siliceous argillites; the radiolarite is green at base and becomes progressively redder up-section. The rock is composed of radiolaria set in a clay-silica matrix that has a small-scale flaser-lamination; small sponge spicules occur rarely. Ammonites found in this lithology by FUGGER 1906 gave its age as Upper Jurassic. The thickness of radiolarite exposed in the Glasenbach Gorge is less than a hundred metres. It is overlain by Gosau conglomerates of Upper Cretaceous age.

Source of "autochthonous" pelagic sediment

Several rock samples from the Glasenbach section have been studied under the stereoscan electron microscope. The presence of *Schizosphaerella* DEFLANDRE & DANGEARD 1938, a planktonic form of unknown systematic position (which is probably identical with *Thoracosphaera* sp. of FISCHER, HONJO & GARRISON 1967), throughout much of the sequence suggests an origin for the pelagic lime mud. This nanno-organism occurs even in the lowest horizon of the Hornsteinkalk exposed in the Glasenbach Gorge (Plate I, Fig. 5) and in many photographs it can be seen in rock-forming quantities (Plate I, Fig. 6). We would thus particularly stress the importance of *Schizosphaerella* as a rock-forming element in Lower and Middle Jurassic pelagic limestones: this organism has also been recorded by BERNOULLI and RENZ 1970 in Jurassic sequences from the Apennines and Greece.

Coccoliths appear, co-existing with *Schizosphaerella,* in the Upper Liassic to Middle Jurassic of the Glasenbach section (Plate I, Fig. 4): such a co-existence may also be found in coeval rocks in the Apennines (BERNOULLI & RENZ 1970). Coccoliths also occur in the Upper Jurassic Radiolarite, but they are not well preserved. Radiolaria are conspicuous in the lower and upper part of the section, becoming of rock-forming importance in the Radiolarite. Sponge spicules constitute another important source of silica, particularly in the Lower Liassic.

We have not undertaken any clay mineral analyses, but HALLAM 1967 records illite with a trace of kaolinite from a Toarcian marl in the Glasenbach Gorge. Both these minerals are probably of continental origin: illite is a common clay mineral in Recent pelagic sediments where it may be of aeolian origin (GRIFFIN, WINDOM & GOLDBERG 1968).

The different silica-carbonate ratios in the section are presumably a function of basin morphology with its consequent effects on carbonate solution, and also of food supply for benthonic sponges; however, they may furthermore be related to the evolutionary life-span of *Schizosphaerella*. This nannofossil has only been found in the Lower and Middle Jurassic (B. PRINS, personal communication, 1969), and might have been particularly important as a sediment contributor during the deposition of the (essentially non-siliceous) Red Nodular Limestones and Marls.

Slump-complexes and turbidites

Slumped beds and slump conglomerates occur frequently within the Fleckenkalk and the Red Nodular Limestones and Marls (Marly Ammonitico Rosso). In the past such structures, which are widespread in the Jurassic of the Austro-Alpine realm, have mainly been interpreted as products of thrusting, disharmonic folding and tectonic brecciation. This latter view, particularly stressed by VORTISCH 1931, 1934, 1937, 1963, 1968; cf. DEL-NEGRO 1957, 1958, has since been questioned by TRÜMPY 1960, GARRISON & FISCHER 1969 and M. and W. SCHLAGER (M. SCHLAGER 1961, 1966; M. SCHLAGER & W. SCHLAGER 1969). The non-tectonic origin of these structures, however, is clearly indicated by plastic deformation and flow of unconsolidated sediment within the slump sheets, by stratigraphic contacts at their top (cf. VORTISCH 1963, p. 363) and by close association with turbidites, which themselves indicate gravitational movement of unconsolidated sediment. Within slumped masses one can find not only penecontemporaneously displaced material but also considerably older lithological elements. This can explain the observations of FUGGER 1906, DEL-NEGRO 1957,1958 and VORTISCH 1963, 1968 whereby rocks containing older faunas are intercalated with younger sediments.

Fleckenkalk

In the Fleckenkalk (1 B) slump complexes more than 15 m thick are present (Plate 5, Fig. 2). Their lithological composition and thickness, however, change laterally very rapidly as does the style of deformation. In most places, a layer of rubbly, retextured sediments is present at the base of the slumped units (Plate 2, Fig. 4). These sediments contain irregularly shaped and deformed pebbles of lime mud exceptionally rich in sponge spicules (usually replaced by ferroan calcite) and with irregularly scattered crinoid ossicles. The pebbles may be embedded in a white crinoid-echinoid biosparite matrix or merge into a fluidally textured matrix of the same composition (Plate 2, Fig. 2 and 4). In part they may represent clasts of fine, only slightly consolidated sediment caught up by the slump mass; others may have originated by accretion during the movement, as is suggested by fluidally textured mantles coating obviously rotated clasts. Intense deformation of the mud may have resulted in a secondary lamination ("Lamellierung", VOIGT 1962); this process is demonstrated by clasts with tails that merge into this secondary fluidal structure. Many pebbles show traces of incipient and irregular chertification which is cut off at the edges of the clasts: this implies derivation of the pebbles. In places, however, chertification has obliterated the boundaries of the clasts and thus must have terminated only after the slump movement took place. Further evidence of this is provided by occasional chert "halos" which cut fluidal laminations of the rock. Post-depositional chertification is also indicated by replacement and cementation of redeposited crinoidal biosparites.

The main part of the slumped complexes comprise rocks in which the original stratification, or traces of it, are still recognisable; and in places the slumped mass consists of a chaotic mélange of large tilted blocks with no internal deformation, which indicates lithification prior to transport (Plate 5, Figs. 2 and 3). In other cases, beds are deformed plastically and pass laterally into retextured sediments. The interstices between blocks and slump-folds are filled with slump-rubble with a "phacoidal" and "lamellar" structure (cf. VOIGT 1962) similar to that described from the base of the slumps. The stratified lithologies comprise fine calcilutites with sponge spicules (often replaced by ferroan calcite), which partly correspond to the underlying Hornsteinkalk, as well as white, well-bedded crinoidal biosparites with nodules of replacement chert. Though these crinoidal rocks do not show any obvious graded bedding, they seem to represent earlier resediments caught up by the slump along with the sponge-spiculid limestones. In some cases the latter might be considerably older than the host rocks as indicated by Lowermost Liassic (Hettangian) faunas in such Hornsteinkalk-complexes (FUGGER 1906; DEL-NEGRO 1957, 1958; VORTISCH 1963).

Apart from the slump-folded complexes, the Fleckenkalk contains thin intercalations of white, slightly graded and laminated crinoid/echinoid biosparites which are strongly recrystallised; these contain a notable admixture of micritic intraclasts. This lithology is locally chertified. It might correspond to the Echinodermenspatkalke that occur in the Allgäu Beds where resedimented conglomerates (JACOBSHAGEN 1964) and associated turbidites also occur (BERNOULLI 1964, p. 61).

Red Nodular Limestones and Marls

In the lower part of the Red Nodular Limestones and Marls (2 A and 2 B) slumped beds similar to those in the Fleckenkalk are present. Intercalations of red pebbly mudstones, between one and three metres thick, also occur; their marly matrix contains sparse limestones nodules occasionally with an internal phacoidal structure (Plate 2, Fig. 1). These rocks might have originated by processes similar to those that formed the retextured sediments described from the Fleckenkalk; however, they may represent more distal parts of slumps as they are much thinner and contain exclusively strongly mobilized sediments. One of the pebbly mudstones has been found to be immediately overlain by a layer of redeposited red crinoidal biosparite containing mud pebbles of fine pelagic limestones with small ammonite shells, ostracods, spicules and occasional echinoderm fragments (Plate 3). This lithology grades upwards into fine crinoidal limestone. The fine groundmass of the mud pebbles contains abundant tests of *Schizosphaerella* as does the "autochthonous" pelagic sediment (Plate 1, Fig. 1). In other cases the pebbly mudstones are overlain by fluidally textured marly calcilutites with sparse, obviously displaced crinoid fragments (the crinoids are pink and the matrix is green, Plate 2. Fig. 3) or by "autochthonous" pelagic sediments.

The "Knollenbreccie" (2 C) constitutes the most spectacular resedimented mass within the Glasenbach section. In the lower part, large parts of the slump are made up of nodular marls and marly limestones, in which traces of bedding are locally preserved and which laterally grade into retextured sediments. Higher up these retextured sediments grade into pebbly mudstones which contain blocks and boulders of lithified limestones. Occasionally slabs of marly limestones occur in which traces of bedding are present. Thin compacted lenses of carbonaceous material may also be found. The boulders and limestone nodules are badly sorted (Plate 4, Fig. 1), but a general decrease of grain size towards the top can be recognized (cf. M. SCHLAGER 1960). Similar relationships have been found in slumped masses overlain by huge boulder beds near Kammerköhr Alm, north of Waidring, Tirol (Plate 3, Fig. 2; cf. GARRISON & FISCHER 1969). The lithic fragments encountered in the "Knollenbreccie" in the Glasenbach Gorge comprise a great variety of limestones of the "Schwellenfazies": (1) red crinoidal biomicrites with abundant foraminifera (Trocholinids, *Involutina liasica* (JONES), *"Vidalina" martana* FARINACCI, *Frondicularia hexagona* TERQUEM a. o.), comparable to the Adnet Limestone s. str., (2) red biomicrites with subsolved relics of ammonite shells (Adnet Limestone s. str.) and (3) red crinoidal biosparites comparable to the Hierlatz Facies. Ammonites from the "Knollenbreccie" sometimes have a ferromanganese coating which shows that they were most probably derived from a "seamount" area.

The top of the "Knollenbreccie" is only badly exposed in the Glasenbach Gorge. However, we think that the highest part of the slump mass might be represented by grey marls which crop out in the lowest part of the Lettenbach (a small southern tributary of the Glasenbach Gorge) and which are overlain by graded marly intramicrites to biomicrites. This turbiditic layer could be genetically linked to the slump mass and could constitute the finest fraction settling out from suspension; such a relationship between slumps and associated turbidites has often been found in pelagic basinal sequences of the Tethyan Jurassic (BERNOULLI 1964, 1969).

Above the "Knollenbreccie" no larger slump masses have been found in the Jurassic of the Glasenbach Gorge. From this interval (2 D and 2 E) HALLAM 1967 has recorded crinoidal limestones that "above a sharply defined base, contain abundant crinoid ossicles and '*Bositra*' valves; the upper part of these beds is finer grained with fewer crinoid remains"; however, HALLAM did not apparently interpret these beds as turbidites. The beds which are up to 30 cm thick contain various proportions of intraclastic and skeletal material and are conspicuously graded (Plate 6, Figs. 3 and 4). At the base, flute casts may be present (Plate 5, Fig. 1) and crinoid fragments are preferentially concentrated in the lower part of the turbidite where they may show imbrication or orientation parallel to the base of the bed (Plate 6, Fig. 3). Pelagic lamellibranchs, however, are the main constituents of the finer fractions and may exhibit ripple-drift lamination (Plate 6, Fig. 2). Pelagic mud pebbles within the turbidites vary in size from a few centimetres to a few millimetres across. In some cases, the turbidites are overlain by thick red marly mudstones without internal structure; these are apparently genetically linked to the turbidites and might represent the finest fraction of the redeposited material (BERNOULLI 1969). Like the pelagic mud pebbles caught up by turbidity currents they contain abundant tests of *Schizosphaerella* and small coccoliths (Plate 1, Fig. 4). Recent pelagic turbidites, with coccoliths in the fine fraction, have been reported by CONOLLY and EWING 1969.

In the upper part of 2 D the turbidites consist almost exclusively of pelagic lamellibranchs with only rare crinoid ossicles (Plate 6, Fig. 1 and 2) and micritic intraclasts.

We have not found any redeposited material in the Radiolarite in the Glasenbach Gorge; however, M. SCHLAGER 1961, 1964 has reported graded microbreccias from the Radiolarite a few kilometres southeast of the Glasenbach Gorge.

Palaeogeographic and environmental synthesis

General

We have described in some detail a basinal Jurassic sequence and, from published descriptions, it is clear that similar successions occur elsewhere in the Eastern Alps (JACOBSHAGEN 1964; M. SCHLAGER & W. SCHLAGER 1969; GARRISON & FISCHER 1969, Figs. 15, 16, 17; and our Plate 4, Fig. 2). These also are characterised by greater thickness than the coeval Adnet Limestone (s. str.) and show evidence of the vicinity of palaeoslopes (slumps, turbidites, etc.). Thus we have a contrast between the more calcareous Adnet "seamount facies" which shows evidence of synsedimentary solution and lithification and contains ferromanganese nodules (GARRISON & FISCHER 1969; ZANKL 1969) — and the more marly Hornstein- and Fleckenkalk and Red Nodular Limestones and Marls which do not exhibit these features to the same extent.

These different types of succession make it clear that we are dealing here with an ancient sea bottom topography that was anything but regular. FUGGER (1906) tentatively recorded the presence of Kössen Beds from the Glasenbach Gorge, but we have not seen them, nor are they recorded by DEL-NEGRO 1957, VORTISCH 1963 or PREY et al. 1969: if present they would imply that the basin was inherited from Rhaetian times (M. SCHLAGER 1967). The seamount source of the turbidites must be sought in slightly submerged blocks of Dachstein Limestone (Adnet "Seamounts").

Evolution of turbidites

The redeposited sediments in the Glasenbach Gorge show an evolutionary pattern: first white intraclastic crinoid-echinoid biosparites in the Fleckenkalk, then pink crinoidal biosparites at the base of the Red Nodular Limestones and Marls, red mixed crinoidal-pelagic lamellibranch biosparites/biomicrites higher up, then finally red pelagic lamellibranch biomicrites/biosparites, with only very rare crinoids, at the top of the Red Nodular Limestones and Marls. This must reflect the paleogeographic evolution of the source area.

From a study of Tethyan crinoidal limestones JENKYNS 1969 suggested that such deposits, in autochthonous position, usually characterised an early shallow-water phase of seamount evolution: thus the pattern of turbidites in the Glasenbach Gorge presumably reflects a slow sinking of the source area. The change from white to red crinoidal limestones is indicative of increasing pelagic influence, with accompanying haematitic mineralisation, at the source area: this effect is, to some extent, mirrored by the change-over from Fleckenkalk to Red Nodular Limestones and Marls in the basinal succession. The incoming of the pelagic lamellibranch turbidites must indicate a depth of the seamounts where the establishment of crinoid gardens was no longer favoured. The turbidite-free radiolarite must indicate elimination of local bottom relief and basin starvation since there is a facies convergence with the Adnet Limestone (s. str.) successions ("seamount" facies) where Upper Jurassic radiolarites also occur (GARRISON & FISCHER 1969; WENDT 1969). In some neighbouring areas, however, considerable topographic relief still existed during the Upper Jurassic, as shown by the presence of slump-complexes, fluxoturbidites and turbidites in the Radiolarite (Tauglbodenschichten, M. SCHLAGER & W. SCHLAGER 1969).

Seamount and basin palaeogeography

The presence of crinoidal turbidites, if derived from the same source, of ages encompassing most of the Liassic, suggests a relative stability of the source area within the general subsidence of the whole area. Moreover, the Adnet Limestone (s. str.) with its numerous hardgrounds and condensed beds (e. g. HIRSCHBERG & JACOBSHAGEN 1965) suggests that the Adnet swells remained more or less sediment-free for much of the Lower and Middle Jurassic (WENDT 1969) and this in turn implies the former presence of a topographic feature that persisted over this period of time. The lack of sedimentation on the top and flanks of this swell or swells might help to explain the prior lithification (see FISCHER & GARRISON 1967; SHINN 1969) of many of the slumped beds and blocks, some of them matchable in the Adnet Limestone (s. str.) successions. In this context the submarine lithification of the "Scheck" (HUDSON & JENKYNS 1969) may also be explained: the presence of a considerable non-sequence above this lithology (WENDT 1969) suggests that after sliding from somewhere upslope (M. SCHLAGER 1961, 1966 and others) the nodules and blocks lay around on the sea floor for a considerable length of time without being covered by much sediment: this must have enabled the sparite to form. Such spar-cemented nodular limestones (see BERNOULLI & RENZ 1970, for a Grecian example) are thus a "Schwellen Fazies" and owe their origin to topographic irregularities within or at the edge of a seamount area. They contrast with the marly "Knollenbreccien" of the Glasenbach Gorge, formed under much higher sedimentation rates. Both the "Scheck" and the large Glasenbach slump mass (2 C) might, however, be related to the same tectonic events.

Depths on the Adnet swell or swells may, for some of its early history (Lower to Middle Liassic) have been within the photic zone, say less than 150 metres (RYTHER 1956); this is indicated by the presence of boring algae within manganese coated blocks in the "Scheck" (WENDT 1969) and by the possible presence of stromatolitic structures in other blocks (Plate 5, Fig. 4). A tentative interpretation of these structures as of algal-mat origin, with later accentuation by ferruginous colloids, does not seem unreasonable since many condensed pelagic Jurassic sequences are associated with algal stromatolites (Radwański & Szulczewski 1965; Szulczewski 1968; Jenkyns & Torrens 1969; Sturani 1969).

As for the depth of the Glasenbach Basin — this was presumably deeper than the photic zone throughout its Jurassic history, and the succession, terminating with radiolarite, must reflect a deepening sequence. We do not think that evidence of aragonite solution, for which there is plenty in the Glasenbach section, is indicative of abyssal depths, however (cf. Garrison & Fischer 1969), since temperature, carbonate supply, carbonate removal, and net sedimentation rates can all affect the solution of calcium carbonate, and it cannot be safely assumed that the present compensation depth for aragonite bears any relation to that in the Jurassic. Some solution of calcium carbonate (aragonite *and* calcite) can take place in Recent oceans at depths as shallow as a few hundred metres (Fischer & Garrison 1967).

Depths in the order of several hundred metres thus seem likely for the Glasenbach Basin, with perhaps considerable increase by the time of Radiolarite deposition.

Comparison with other Tethyan locations

We are impressed by the resemblance of the Glasenbach succession to many pelagic sequences in the Southern Alps, the Central Apennines, and Western Greece; in this context the Hornsteinkalk may be equated with the Lombardian Kieselkalk, the Fleckenkalk with the Corniola and the Siniais Limestone, the Red Nodular Limestones and Marls with the Toarcian-Aalenian "Ammonitico Rosso", and the Radiolarite with the Upper "Posidonia" Beds and the "Scisti ad Aptici"; and, in fact, a similar evolution of turbidites may be recognised in these sequences (see Bernoulli 1967, 1969). Obviously palaeogeographic situations in the Eastern Alps were by no means unique, but reflected a tectonic evolution that was common to many environments on the southern continental margin of the Tethys. For many of these environments synsedimentary block-faulting seems to have been both the most important cause of facies differentiation and a triggering agent for gravitational mass movements (Bernoulli 1969). Repeated rejuvenation of sea-floor topography is indicated by basinal sediments, including turbidites, involved in slump movements.

The progressive reduction in benthos and general increase in the amount of red sediment up the section must reflect a decrease in organic matter on the sea floor. This may not only be a function of increasing depth (Garrison & Fischer 1969) but also of increasing distance from land (cf. Hallam 1967). Such a mounting pelagic influence may well be related to an expanding Tethyan Ocean.

Conclusions

The Glasenbach Gorge exemplifies a pelagic basinal Jurassic sequence. The lithologies comprise marls, limestones and cherts. The pelagic lime mud seems to have been predominantly derived from planktonic organisms (coccoliths, *Schizosphaerella*), the silica from sponge spicules and radiolaria; the clay minerals are presumably of detrital origin.

Turbidites, sometimes involved in slump folds and slump conglomerates, occur in parts of the sequence; they reflect the palaeogeographic evolution of their source areas, becoming more "pelagic" up-section.

This basinal sequence contrasts with the Adnet Limestone (s. str.) which is a condensed limestone affected by penecontemporaneous solution and lithification, and enriched in ferromanganese oxides. The submarine highs, "seamounts", on which the Adnet Limestone formed, were probably the source areas for the Glasenbach slump conglomerates and turbidites.

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PLATE 1

1. Micritic groundmass of pelagic mud pebble from crinoidal fluxoturbidite, showing *Schizosphaerella* DEFLANDRE and DANGEARD, 1938 (form with few layers), in neomorphically formed (?) calcite matrix. ×2000 (Sample DB 3478, cf. Plate 3).
   Red Nodular Limestones and Marls (2 A).
   Middle Liassic.
2. Micritic groundmass of pelagic mud pebble in pelagic lamellibranch turbidite, composed almost entirely of tests of *Schizosphaerella* (many layered form) and their debris, ×2000 (Sample DB 3541, cf. Plate 6, Fig. 1).
   Red Nodular Limestones and Marls (2 D).
   Upper Liassic—Middle Jurassic.
3. Micritic groundmass of pelagic mud pebble in crinoidal turbidite, mainly composed of *Schizosphaerella* (both forms), ×2000 (Sample DB 3530, cf. Plate 6, Fig. 3).
   Red Nodular Limestones and Marls (2 D).
   Upper Liassic—Middle Jurassic.
4. Groundmass of red marly mudstones, overlying crinoidal turbidite, containing small coccoliths and debris of *Schizosphaerella*, ×5000 (Sample DB 3371).
   Red Nodular Limestones and Marls (2 D).
   Upper Liassic—Middle Jurassic.
5. Groundmass of "autochthonous" pelagic sediment in Hornsteinkalk. Badly preserved *Schizosphaerella* in neomorphically formed calcite, ×2000 (Sample DB 3451).
   Hornsteinkalk (1 A).
   Lower Liassic.
6. Micritic groundmass of "autochthonous" pelagic sediment in Fleckenkalk, composed almost entirely of *Schizosphaerella*, ×1000 (Sample DB 3458).
   Fleckenkalk (1 B).
   Lower—? Middle Liassic.

Stereoscan electron micrographs of limestone fracture surfaces. All specimens from the Glasenbach Gorge, Salzburg, Austria.

TAFEL 1

1. Mikritische Grundmasse eines pelagischen Kalkschlammgerölls aus einem Fluxoturbidit. *Schizosphaerella* DEFLANDRE und DANGEARD, 1938 (Form mit wenigen Lagen) in neomorpher (?) Kalzit-Grundmasse. 2000× (Probe DB 3478, vgl. Tafel 3).
   Rote knollige Kalke und Mergel (2 A).
   Mittlerer Lias.
2. Mikritische Grundmasse eines pelagischen Kalkschlammgerölls aus einem Turbidit mit pelagischen Lamellibranchiaten. Die Grundmasse wird fast ausschließlich von *Schizosphaerella* (Form mit vielen Lagen) und ihren Skelettelementen aufgebaut. 2000× (Probe DB 3541, vgl. Tafel 6, Fig. 3).
   Rote knollige Kalke und Mergel (2 D).
   Oberer Lias—Dogger.
3. Mikritische Grundmasse eines pelitischen Kalkschlammgerölls aus einem Turbidit mit Crinoiden-Fragmenten. *Schizosphaerella* (beide Formen). 2000× (Probe DB 3530, vgl. Tafel 6, Fig. 3).
   Rote knollige Kalke und Mergel (2 D).
   Oberer Lias—Dogger.
4. Grundmasse eines roten Mergels, unmittelbar über Crinoiden-Turbidit. Kleine Coccolithen und zerfallene Skelettelemente von *Schizosphaerella*. 5000× (Probe DB 3371).
   Rote knollige Kalke und Mergel (2 D).
   Oberer Lias—Dogger.
5. Grundmasse des „autochthonen" pelagischen Sedimentes der Hornsteinkalke. Schlecht erhaltene Skelette von *Schizosphaerella* in neomorphem Kalzit. 2000× (Probe DB 3451).
   Hornsteinkalk (1 A).
   Unterer Lias.
6. Mikritische Grundmasse des „autochthonen" pelagischen Sedimentes der Fleckenkalke, nahezu ausschließlich von Skeletten von *Schizosphaerella* aufgebaut. 1000× (Probe DB 3458).
   Fleckenkalk (1 B).
   Unterer—? Mittlerer Lias.

Stereoscan Elektronen-Mikroskop-Aufnahmen von frischen Bruchflächen. Alle Proben stammen aus der Glasenbach-Schlucht, Salzburg, Österreich.


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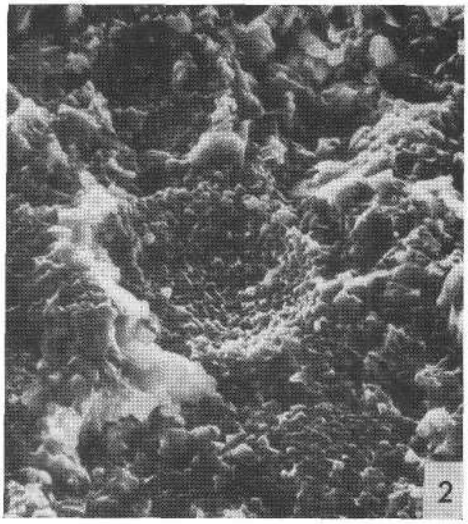
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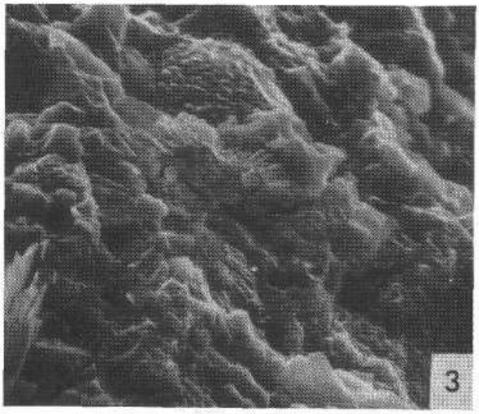
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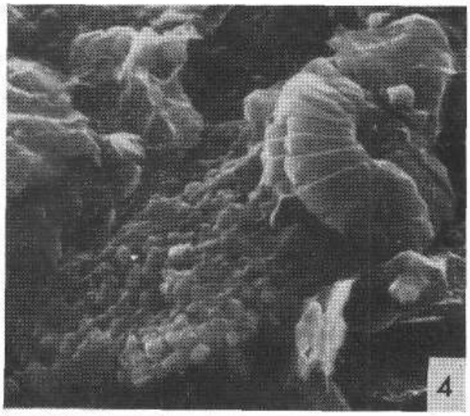
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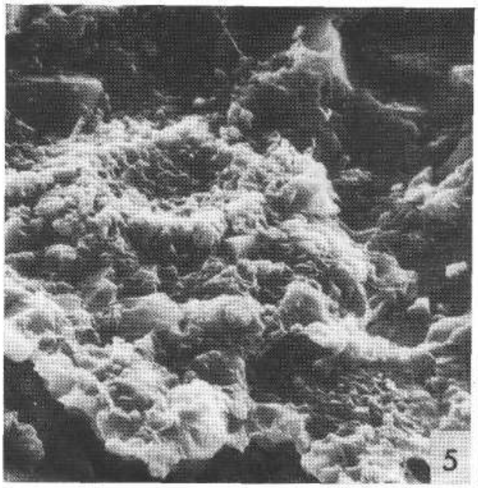
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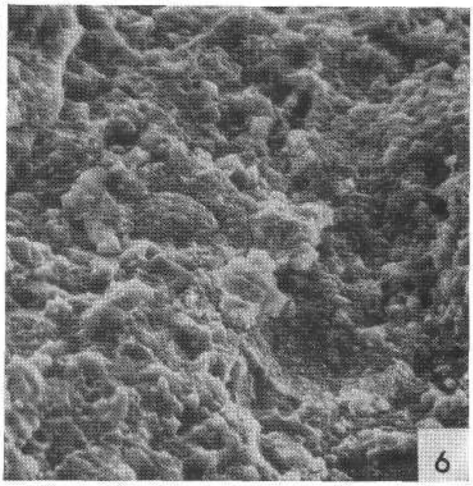
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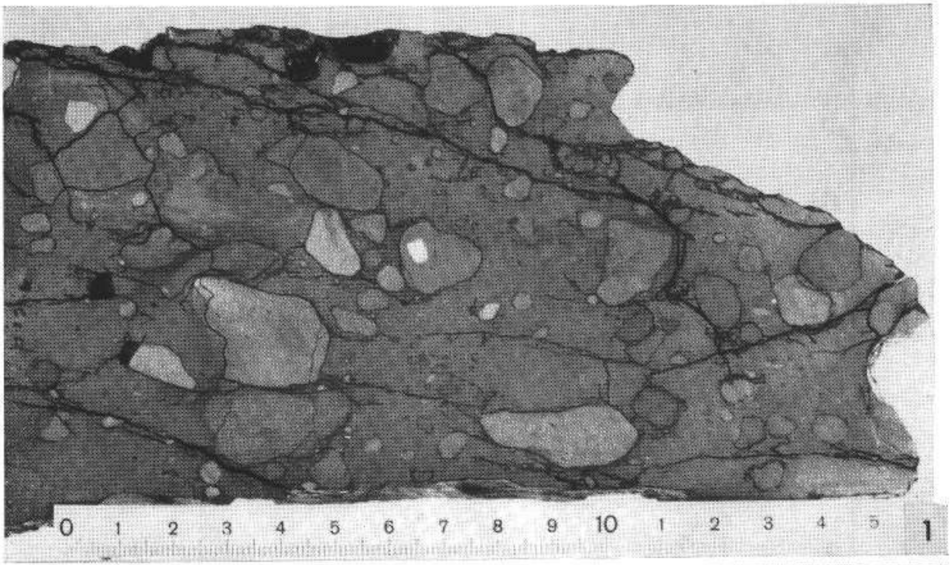
PLATE 2

1. Red pebbly mudstone. Dark red marly matrix with sparse nodules of pelagic limestone which partly merge into the homogeneous or fluidally textured matrix (black sutures are later cracks filled with araldite). This lithology is overlain by fluidally textured marly mudstones with sparse crinoid ossicles (3).
   Red Nodular Limestones and Marls.
   Middle Liassic.
   Glasenbach Gorge, Salzburg, Austria (sample DB 3495). Polished surface.
2. Marly biomicrite with abundant sponge spicules. Note spicule-poor pebble merging into groundmass in upper right and incipient chert nodule in lower part of photograph.
   Fleckenkalk.
   Lower Liassic—? Middle Liassic.
   Glasenbach Gorge, Salzburg, Austria (sample DB 3474). Negative print from thin-section, ×5.
3. Single displaced crinoids (pink) in fluidally textured matrix of green marly biomicrite. This lithology overlies pebbly mudstone illustrated above (1.).
   Red Nodular Limestones and Marls.
   Middle Liassic.
   Glasenbach Gorge, Salzburg, Austria (sample DB 3491). Negative print from acetate peel, ×7.
4. Plastically deformed grey and white marly biomicrites with rotated mud pebbles showing internal deformation. The laminar texture is not primary but results from early diagenetic sediment flow.
   Fleckenkalk.
   Lower—? Middle Liassic.
   Glasenbach Gorge, Salzburg, Austria (sample DB 3474). Polished surface.

TAFEL 2

1. Roter „Geröllmergel" (pebbly mudstone). In einer dunkelroten, mergeligen Matrix schwimmen knollige Komponenten von helleren pelagischen Kalken, welche zuweilen kontinuierlich in die homogene oder fluidal texturierte Grundmasse übergehen. Das Gestein wird von fluidal texturierten mergeligen Biomikriten mit einzelnen Crinoiden-Fragmenten überlagert (3.).
   Rote knollige Kalke und Mergel.
   Mittlerer Lias.
   Glasenbach-Schlucht, Salzburg, Österreich (Probe DB 3495), Anschliff.
2. Mergeliger Biomikrit mit Schwammnadeln. Biogen-arme Komponenten (rechts oben) gehen kontinuierlich in die Nadeln-reiche Grundmasse über. Beginnende Verkieselung im Bild unten.
   Fleckenkalk.
   Unterer Lias—? Mittlerer Lias.
   Glasenbach-Schlucht, Salzburg, Österreich (Probe DB 3474). Negativkopie von Dünnschliff, 5×.
3. Einzelne resedimentierte Crinoiden-Stielglieder (rötlich) in fluidaler Matrix von grünlichem, mergeligem Biomikrit. Dieses Gestein überlagert den Geröllmergel von Fig. 1.
   Rote knollige Kalke und Mergel.
   Mittlerer Lias.
   Glasenbach-Schlucht, Salzburg, Österreich (Probe DB 3491). Negativkopie von Acetatfolie, 7×.
4. Plastisch deformierter grauer und weißer Biomikrit mit rotierten Kalkschlammgeröllen, welche z. T. Spuren interner Deformation zeigen. Die laminare Textur ist keine Ablagerungs-Textur sondern entstand durch Fließen des Sediments während der frühen Diagenese.
   Fleckenkalk.
   Unterer Lias—? Mittlerer Lias.
   Glasenbach-Schlucht, Salzburg, Österreich (Probe DB 3474). Anschliff.



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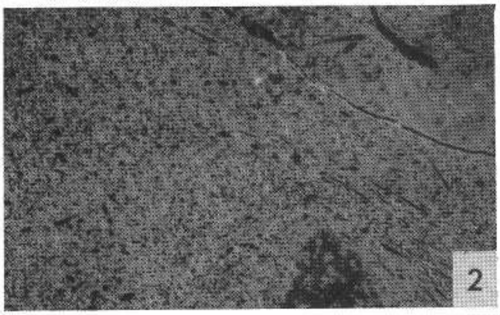

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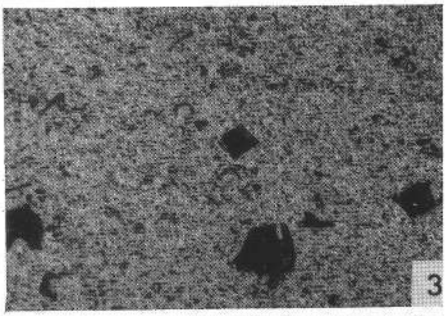

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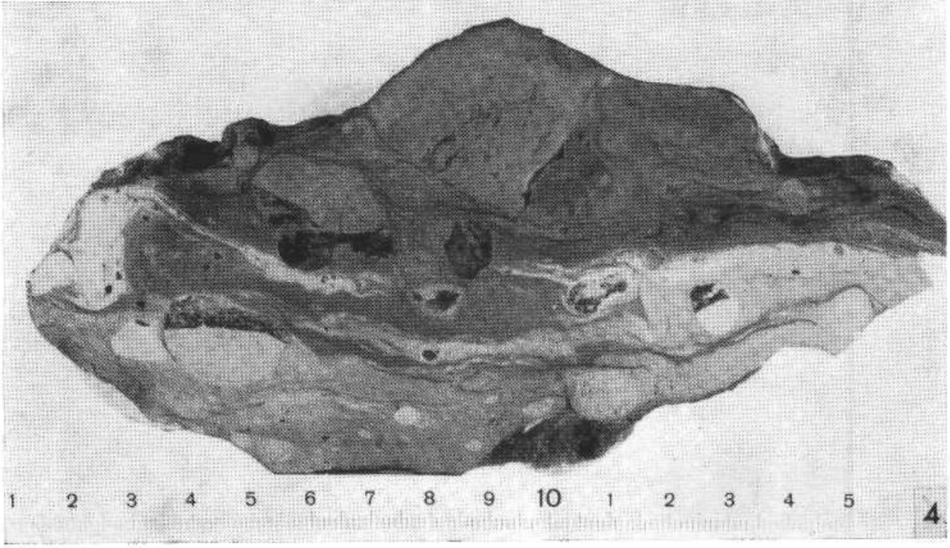

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PLATE 3

Crinoidal biosparite containing lumps of fine biomicrite. As shown by the irregular outlines of the lumps and by the crinoid fragments caught up into their border zones, the lumps were lithified only after final deposition. Early syntaxial overgrowth cement is iron-free calcite and only late calcite cement is ferroan (cf. EVAMY and SHEARMAN, 1969).
This lithology overlies a red pebbly mudstone and grades upwards into fine crinoidal limestone.
Red Nodular Limestones and Marls (2 A).
Middle Liassic.
Glasenbach Gorge, Salzburg, Austria (sample DB 3478). Negative print from thin-slide, ×5.

TAFEL 3

Crinoiden-Biosparit mit Schlammgeröllen von feinem Biomikrit. Die unregelmäßigen Umrisse der Schlammgerölle sowie die randlich eingedrungenen Crinoidenfragmente zeigen, daß die Schlammgerölle bei der Ablagerung des Gesteins noch nicht verfestigt waren. Früher syntaxialer Zement ist Eisen-frei und wird von späterem syntaxialem Fe^{+2}-haltigem Kalzit abgelöst.
Das Gestein überlagert ein rotes Rutschungskonglomerat und geht nach oben in feinen Crinoidenkalk über.
Rote knollige Kalke und Mergel (2 A).
Mittlerer Lias.
Glasenbach-Schlucht, Salzburg, Österreich (DB 3478) Dünnschliff, Negativkopie, 5×.

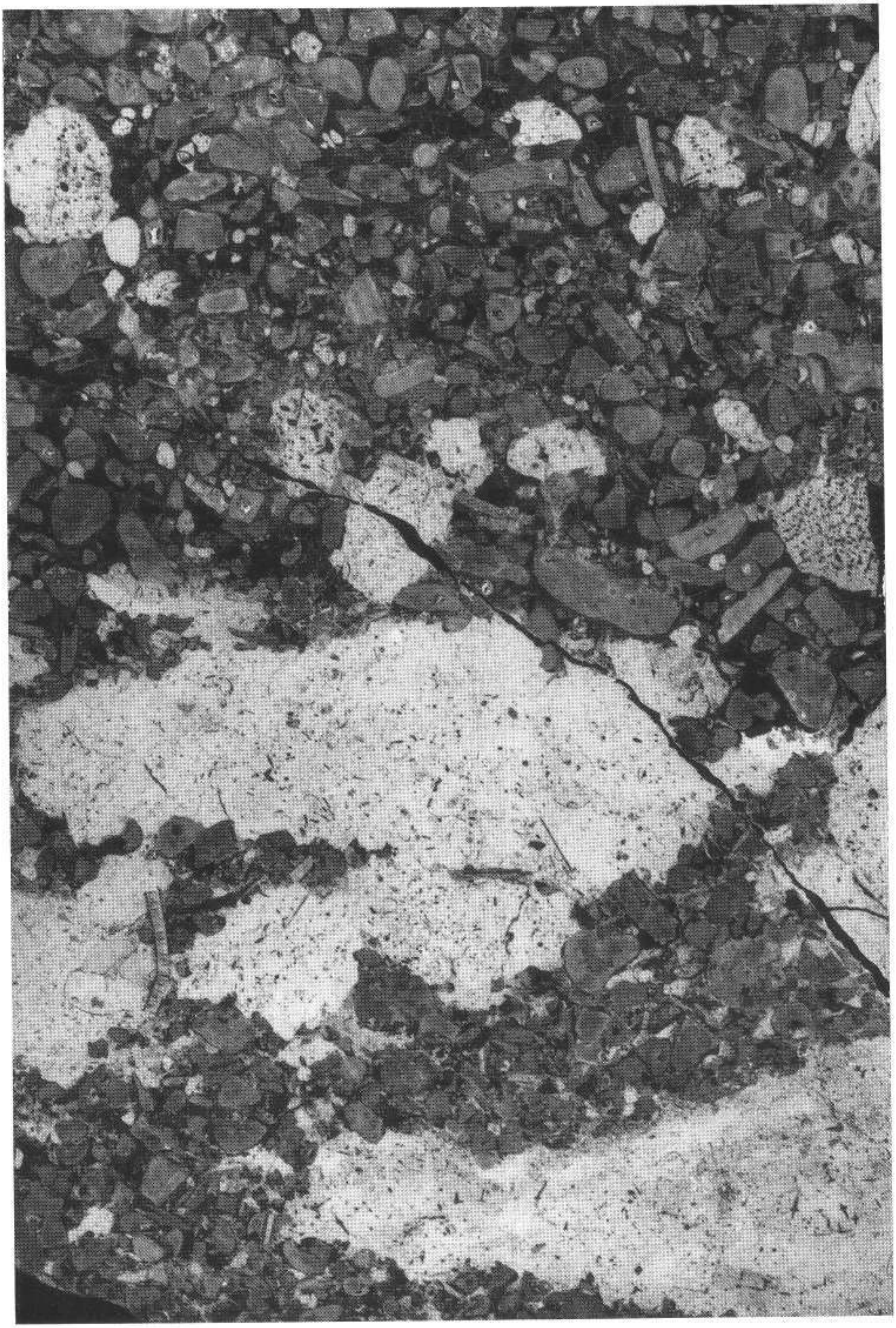

PLATE 4

1. Slump-rubble containing large blocks of limestone in a marly pebbly matrix. Largest block is about 30 cm across. "Knollenbreccie" (2 C).
   Red Marly Limestones and Marls.
   Middle Liassic (Domerian).
   Glasenbach Gorge, Salzburg, Austria.
2. Slumped beds of red nodular limestones and marls grading into retextured sediments which, higher up, contain boulders and pebbles of previously lithified limestones.
   Red Nodular Limestones and Marls (Adnet Beds of GARRISON and FISCHER, 1969).
   Kammerköhr Alm, north of Waidring, Tirol, Austria.

TAFEL 4

1. Rutschungs-Konglomerat mit Kalk-Blöcken in mergeliger, konglomeratischer Grundmasse. Der größte Block (im Bild) ist ca. 30 cm breit. „Knollenbreccie" (2 C).
   Rote knollige Kalke und Mergel.
   Mittlerer Lias (Domerian).
   Glasenbach-Schlucht, Salzburg, Österreich.
2. Rutschpakete von roten, knolligen Kalken und Mergeln, welche kontinuierlich in Geröllmergel übergehen. Im oberen Teil enthalten die Geröllmergel Blöcke und kleinere Komponenten von bereits früher verfestigten Kalken.
   Rote knollige Kalke und Mergel (Adneter Schichten von GARRISON und FISCHER, 1969).
   Kammerköhr Alm, nördlich Waidring, Tirol, Österreich.

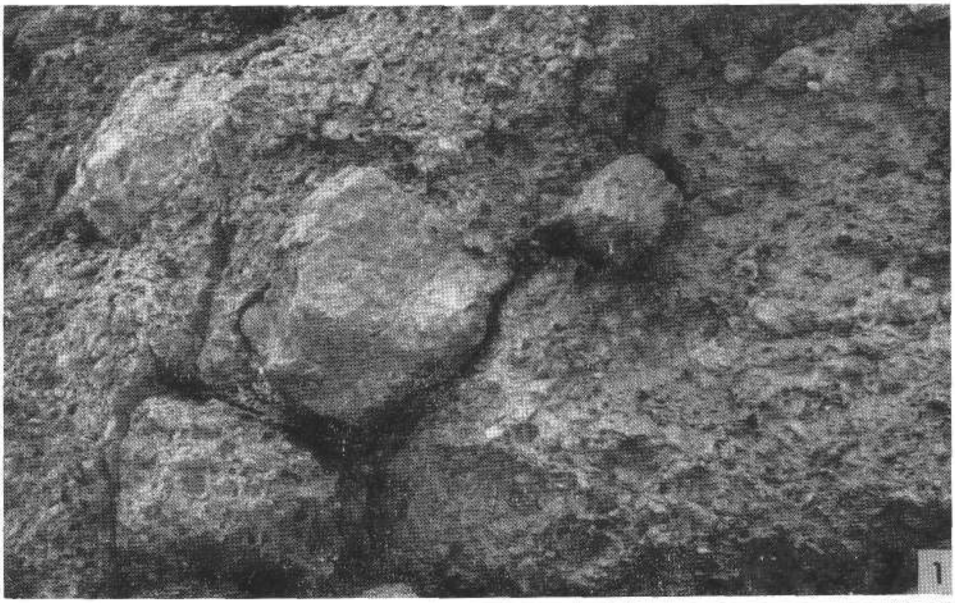

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PLATE 5

1. Flute casts in crinoidal-pelagic lamellibranch turbidite illustrated in Plate 6, Figs. 3 and 4. The flute casts indicate a current direction from west to east. Scale: match in lower right corner.
   Red Nodular Limestones and Marls (2 D).
   Upper Liassic—Middle Jurassic.
   Lettenbach near Pt. 485, Glasenbach Gorge, Salzburg, Austria.
2. and 3. Tilted blocks of stratified limestones in slump-complex. Such beds without internal deformation indicate differential submarine lithification prior to slump movement. Note the stratigraphically undisturbed beds passing above these blocks (Fig. 2).
   Fleckenkalk (1 B).
   Lower Liassic—? Middle Liassic.
   Glasenbach Gorge, Salzburg, Austria.
4. Block with ? stromatolitic clumps (subtidal) picked out by migration of ferruginous colloids. Length of block: 25 cm.
   "Scheck" (Adnet).
   Middle Liassic.
   Polished surface in main hall of Salzburg railway station.

TAFEL 5

1. „Flute casts“ an der Basis eines Turbidits, welcher als Komponenten Crinoiden und pelagische Lamellibranchiaten führt (siehe Tafel 6, Fig. 3 und 4). Strömungsrichtung von Westen nach Osten.
   Rote knollige Mergel und Kalke (2 D).
   Oberer Lias—Dogger.
   Lettenbach, wenig oberhalb Pt. 485, Glasenbach-Schlucht, Salzburg, Österreich.
2. und 3. Gekippte Blöcke von geschichteten Kalken in submariner Rutschung. Diese Blöcke, die keine interne Deformation zeigen, sind Anzeichen von teilweiser submariner Lithifizierung vor dem Zeitpunkt der Rutschung. Überlagernde Schichten in Fig. 2 sind ungestört.
   Fleckenkalke (1 B).
   Unterer—? Mittlerer Lias.
   Glasenbach-Schlucht, Salzburg, Österreich.
4. Block mit fraglichen stromatolithischen Laminae, abgebildet durch Migration von kolloidalen Eisenverbindungen. Länge des Blocks: 25 cm.
   „Scheck“ (Adnet).
   Mittlerer Lias.
   Halle, Hauptbahnhof Salzburg.


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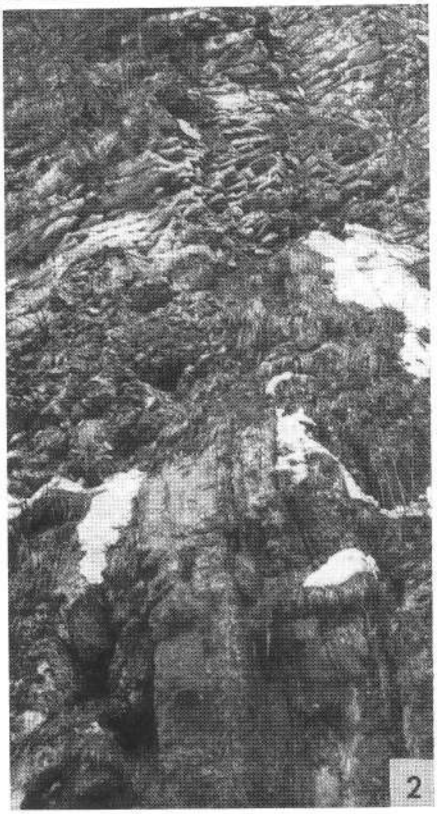
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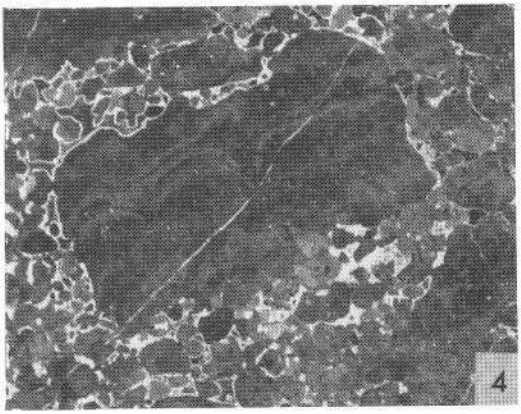
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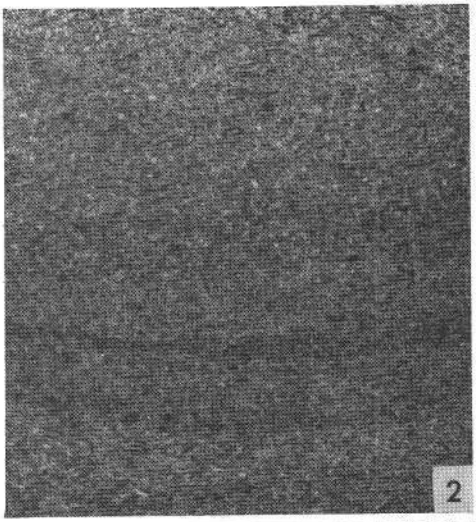
PLATE 6

1. and 2. Graded calcarenite-calcisiltite. In the basal part of the bed (1.) mainly micritic intraclasts (Plate 1, Fig. 2), pelagic lamellibranchs and a few crinoid ossicles are present. The fine fraction (2.) comprises mainly pelagic lamellibranchs, orientated parallel to small-scale current-lamination, calcitised radiolaria and some terrigenous silt.
   Red Nodular Limestones and Marls (2 D).
   Upper Liassic—Middle Jurassic.
   Glasenbach Gorge, Salzburg, Austria (samples DB 3541 and 3542). Negative-prints from thin-sections, ×5.
3. and 4. Crinoidal turbidite. The coarse fraction is mainly composed of crinoid ossicles and pelagic mud intraclasts (Plate 1, Fig. 3). At the base of the bed the crinoid ossicles are either orientated parallel to the bedding or imbricated. Locally the components are closely packed and solution-welded, in other places the crinoid ossicles show syntaxial overgrowth with a recrystallised ferroan calcite matrix. The fine fraction (4.) contains mainly parallel orientated pelagic lamellibranchs, calcitised radiolaria, a few crinoid ossicles and a trace of terrigenous silt. Note graded bedding in 4.
   Red Nodular Limestones and Marls (2 D).
   Upper Liassic—Middle Jurassic.
   Glasenbach Gorge, Salzburg, Austria (samples DB 3530 and 3531). 3. Negative-prints from acetate peel, 4. from thin-section, both ×6, 5.

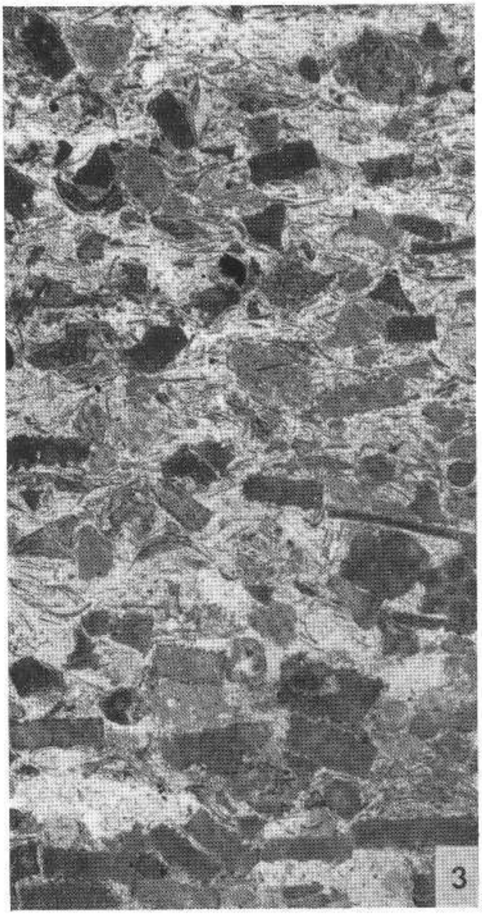
TAFEL 6

1. und 2. Gradierter Kalkarenit bis Kalzisiltit (Turbidit). An der Basis (1.) finden sich hauptsächlich mikritische Intraklasten (s. Tafel 1, Fig. 2), pelagische Lamellibranchiaten und wenige Crinoiden-Fragmente. Die feine Fraktion (2.) besteht hauptsächlich aus eingeregelten pelagischen Lamellibranchiaten, kalzitisierten Radiolarien und wenig terrigenem Silt.
   Rote knollige Kalke und Mergel (2 D).
   Oberer Lias—Mittlerer Jura.
   Glasenbach-Schlucht, Salzburg, Österreich. Negativkopien von Dünnschliffen, 5×.
3. und 4. Bioklastischer Turbidit. Die grobe Fraktion besteht aus Crinoiden-Skeletteilen und pelagischen Intraklasten (s. Tafel 1, Fig. 3). An der Basis sind die Crinoiden parallel zur Schichtung eingeregelt oder dachziegelartig übereinander geschoben. Zum Teil sind die Komponenten dicht gepackt und durch Drucklösungs-Kontakte verschweißt, zum Teil liegen sie in einer rekristallisierten Matrix von Fe^{+2}-reichem Kalzit; in diesem Fall sind die Crinoiden von syntaxialem Zement umkleidet. Die feine Fraktion (4.) enthält hauptsächlich eingeregelte pelagische Lamellibranchiaten, kalzitisierte Radiolarien, wenige Crinoiden-Fragmente und Spuren von terrigenem Silt. Auch die feine Fraktion läßt klares „graded bedding“ erkennen.
   Rote knollige Kalke und Mergel (2 D).
   Oberer Lias—Mittlerer Jura.
   Glasenbach-Schlucht, Salzburg, Österreich. 3. Negativkopie von Acetatfolie, 4. Negativkopie von Dünschliff, 6, 5×.

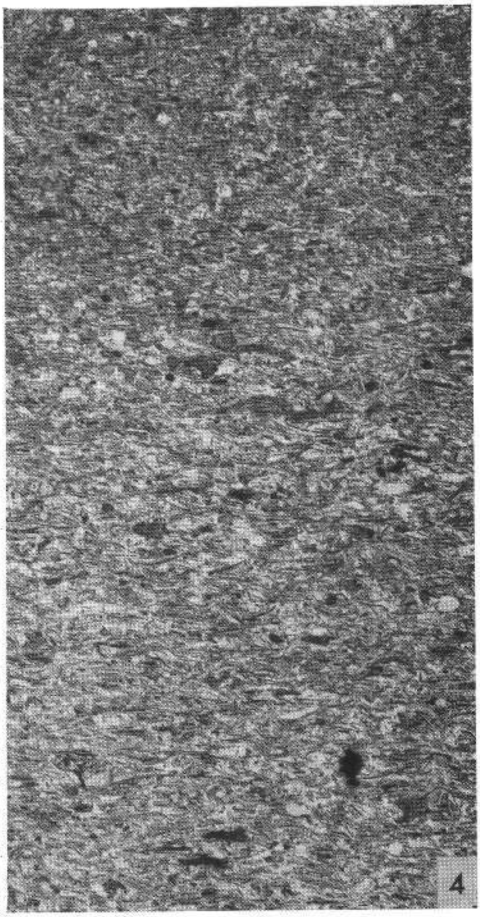
1



2



3



4

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Autor(en)/Author(s): Bernoulli Daniel, Jenkyns Hugh C.

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