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A LOWER LIASSIC OFFSHORE BAR ENVIRONMENT, CONTRIBUTION TO THE SEDIMENTOLOGY OF THE LUXEMBURG SANDSTONE[1]

by

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(10 figures and 2 tables)

RESUME.- Dans le quart NE du Bassin parisien les sédiments arénacés des Grès du Luxembourg sont insérés dans le faciès lorrain du Lias inférieur. Les faunes en place ou remaniées indiquent un milieu de dépôt subtidal. Le transport des sédiments à travers le détroit marin du Sillon eifelien vers le Bassin de Paris s'est effectué par des courants tidaux prédominant dans une direction et qui masquent largement les effets des courants de retour. Dans l'ouest et le sud du Grand-Duché ainsi que dans le Luxembourg belge on constate également les effets produits par des courants induits par des tempêtes. L'affleurement de Reckange/Mersch montre les caractéristiques lithologiques et sédimentaires typiques des Grès du Luxembourg. On y distingue six lithotypes principaux. Les teneurs en carbonate peuvent atteindre 80 o/o et possèdent généralement une origine bioclastique. Bien que des processus diagénétiques sont évidents, ils n'expliquent pas à eux seuls les variations verticales des teneurs en carbonate. Les structures sédimentaires comportent des stratifications obliques à pendage opposé, des surfaces de réactivation sédimentaire, des interlits couplés d'argile ainsi que des flaques argileuses. Ces structures et les populations granulométriques plaident pour un milieu marin peu profond où les remaniements ont été fréquents. Dans ce milieu de "offshore sand waves" s'inscrivent six sub-environnements qui connaissent dans l'aire de répartition des Grès du Luxembourg une distribution caractéristique.

ABSTRACT.- In the northeastern quadrant of the Paris Basin the arenaceous sediments of the Luxemburg Sandstone form part of the Lorraine facies of the Lower Lias. The autochthonous as well as the allochthonous fauna elements indicate a subtidal environment. The sediment transport through the marine channel of the Eifel Depression into the Paris Basin has been effected by tidal currents flowing predominantly in one direction. In West- and South-Luxemburg as well as in Belgium these tidal currents effects have been modified by wave (storm) induced currents. The Reckange locality (Luxemburg) for example shows the lithological caracteristics and sedimentary features typical of the Luxemburg Sandstone. 6 Main lithotypes have been distinguished. The carbonate content of these lithotypes reaches 80 o/o and usually has its source in bioclastic shell fragments. Even thoug early to late diagenetic processes are obvious, they are not wholly capable of explaining the vertical variations in carbonate content. The sedimentary structures show herringbone cross sets with bidirectional dipping foresets, reactivation surfaces, tidal couplets and mud drapes caused by tidal currents. The frequent erosive surfaces as well as the grain size distribution curves suggest hydrodynamic conditions of a shallow marine shelf environment with wave influenced reworking and resedimentation. In this offshore sand wave environment 6 subenvironments can be recognised with a characteristic distribution pattern and varying thicknesses in the several areas of the Luxemburg Sandstone.

1.- INTRODUCTION

The Luxemburg sandstone outcrop in the NE of the Paris Basin extends about 150 km from the southern Eifel in Germany (Südeifel) via Luxemburg (Gutland) towards Belgium (Gaume) in the west. To the south the Luxemburg sandstone expands from the southern Eifel about 70 km through Luxembourg (Gutland) up to the region of Hettange in France (fig. 1). The Caenozoic uplift of the rheno-ardennic massif (Berners, 1983, in press) caused erosional action, limiting the outcrop of the Luxemburg sandstone to the north and east. The diachronous lensing of the sandbody is exposed in

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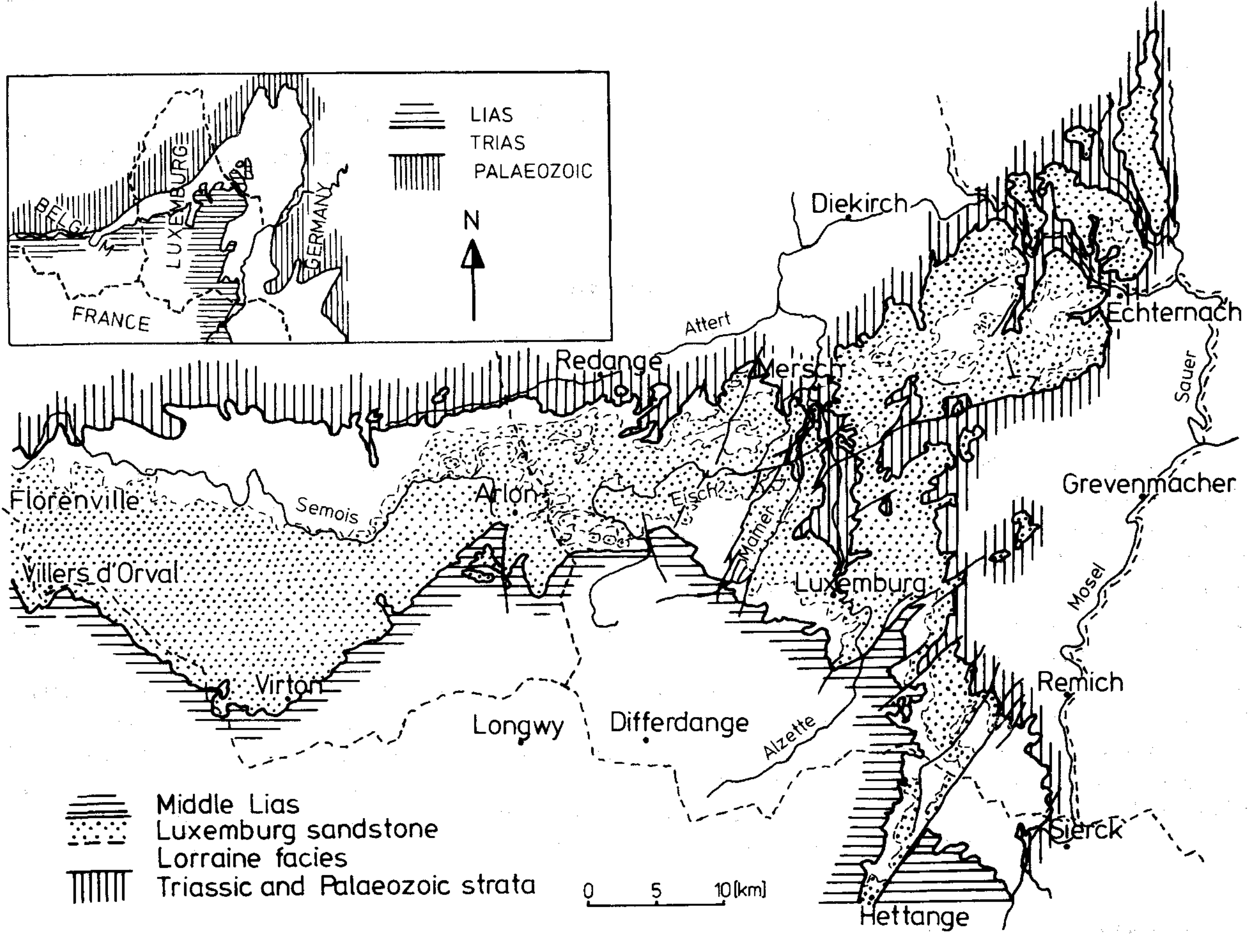

Figure 1
The outcrop of the Lower Lias (Lorraine facies/Luxemburg sandstone facies) in the studied area of the northeastern Paris Basin.

NW- and SE-Luxemburg, while to the southwest the Luxemburg sandstone plunges under younger sediments, where for instance in Longwy and Differdange drilled thicknesses up to 100 m were surveyed (Lucius, 1948).

Depending on the dimensions of the studied area regionally limited geological-sedimentological investigations were continously carried out at the Rhine-Westfalian technical University of Aachen (Lehr- und Forschungsgebiet allg. und hist. Geologie) since 1960. The findings of these investigations were published in several publications as Bintz & Muller (1974); Muller & Rasche (1971); Muller, Parting & Thorez (1973); Muller (1974) ; Preugschat (unpublished) (1) ; Schreck (unpublished) (2) and Muller (1980). A comprehensive digest of all data is done in a current thesis (Berners, in preparation).

More than 1500 samples have been taken in 63 exposures and 3 borings. These outcrops are distributed to the regions of the southern Eifel (6 outcrops), NE-Gutland (12 outcrops), E-Gutland (19 outcrops), SE-Gutland (15 outcrops), W-Gutland (9 outcrops) and the Gaume (5 outcrops). The investigations have been concentrated to the region of Luxemburg, because the lithological and stratofacial development of the

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(1) PREUGSCHAT, F., 1976. Ein Schüttungsmodell des Luxemburger Sandsteins in der Mulde von Weilerbach (Luxemburg). Untersuchungen der Ichno- und Körperfossilien, der Quartzkornoberflächen und der durch die Clusteranalyse strukturierten Granulometrie des Sandsteins. Doctoral thesis, Rhine-Westfalian technical University of Aachen, 157 p.

(2) SCHRECK, H., 1976. Ein Schüttungsmodell des Luxemburger Sandsteins in der Mulde von Weilerbach (Luxemburg). Untersuchung der Schwerminerführung, Schrägschichtung, des Geröllspektrums und der durch die Faktorenanalyse aufschlüsselten Granulometrie des Sandsteins. Doctoral thesis, Rhine-Westfalian technical University of Aachen, 168 p.

outcrops from the southern Eifel is analogous to those of the NE-Gutland (Preugschat, unpublished (1) ; Schreck, unpublished (2) and the outcrops from the Gaume are similar to those of W-Gutland (Berners, 1981).

2.- GEOLOGIC AND STRATIGRAPHIC RANGE OF THE LUXEMBURG SANDSTONE

With reference to the generell regressive phase in the Upper Triassic the Liassic transgression in the NE of the Paris Basin develops with shallow marine sediments of the Lorraine facies (Muller, 1980). Into this limestone - marl - clay interstratification the offshore bars of the calcareous Luxemburg sandstone are lenticular inserted (Muller, 1974). Between the lenses of sand bars thin recurrences of the Lorraine facies are possible (Berners, unpublished) (3).

The Luxemburg sandstone is characterized by a fine to medium grained, well or very well sorted sediment. The content of carbonate comes up to 80 o/o. Pebbles and fossil debris bearing sandstones (ammonites, echinoderms, foraminifers, gastropods, corals, lamellibranchs) are inserted. The non-carbonatic grains of the sand/silt fraction are of high lithological and textural maturity and consist usually of solitary quartz. The amount of quartzitic rock fragments is lower than 10 o/o (Berners, unpublished). (3). Feldspars and micas have been detected only in traces. Also the stable heavy mineral association (Schreck, unpublished) (2) proves that the non-carbonatic particles of the sandstone have its source in older, polycyclic sediments. At the base of the sandstone a continuous sanding up is developed. In most cases its top shows a sharp boundary, which is locally colonized by sessile, boring animals, forming a hardground called "surface taraudée" (Lucius, 1948).

The sandy sediments had been transported to the south through the marine channel of the Eifel-depression (Eifeler N-S Zone) and had been accumulated on the shallow marine shelf of the northeastern Paris Basin (Muller, 1980). The Eifel-depression, which had been established in the beginning Mesozoic, represents in respect of the Paris Basin an important transgression zone, which was effective in the Middle Triassic (Schrader, unpublished) (4), but above all in the Rhaetic (Hendriks, unpublished) (5) and in the Lower Lias. In consequence of the Liassic transgression the sand bar shifted to the NW up to the Ardennian continent. The diachroneity from east to west in younger stratigraphic horizons appearing sanding up comprises the ammonite zones of Hettangian and Sinemurian age (fig. 2, after Muller, 1980).

The shifting of the sand-lenses had been controlled by synsedimentary tectonic structures, being active again during the Caenozoic uplift of the Rheno-ardennic massif. Especially the NE-SW orientated lineament near Longwy-Kopstal-Echternach (fig. 2) provides this statement. Here, during the Upper Hettangian, a fast displacement of the area of sedimentation took place, as verified by the westward shifting of the sand bars from the beginning of the *Angulata*-zone to the beginning of the *Rotiforme*-zone (fig. 2b). Also the eastern margin of the area of sedimentation at the beginning of the *Bucklandi*-zone has been associated in the southwestern Gutland with this tectonic lineament. In recent times the region of this synsedimentary active lineament corresponds to the uplifted block of Born, while the region in the north and northwest of this uplifted block, where the sand accumulation stayed during the *Angulata*-zone up to the *Bucklandi*-zone, could be compared to the in recent times still downthrown block of Weilerbach (Lucius, 1948). In the southeastern part of Luxemburg the synsedimentary active, NE-SW orientated tectonic structures are obvious and comparable to recent faults. Here the lensing from a thickness of 70 m to 0 m takes place at a lateral distance of only 5 km (Bintz & Muller, 1966).

3.- THE SEDIMENTOLOGY OF THE LUXEMBURG SANDSTONE

3.1.- METHODS AND AIM OF THE INVESTIGATION

Different sedimentological investigations will allow the reconstruction of the environment of the Luxemburg sandstone. Similarities to recent environments, as

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(3) BERNERS, H.P., 1981. Faziesuntersuchungen im Luxemburger Sandstein West-Luxemburgs. Unpublished masters thesis, Rhine-Westfalian technical University of Aachen, 154 p.

(4) SCHRADER, E., 1983. Ein Sedimentationsmodell der Trias in der Eifeler Nord-Süd-Zone unter besonderer Berücksichtigung der Nordeifel (Mechernich-Maubacher Triasdreieck). Doctoral thesis, Rhine-Westfalian technical University of Aachen, 300 p.

(5) HENDRIKS, F., 1982. Ein Modell der Rätsedimentation am Ostrand des Pariser Beckens ; Untersuchungen zur Granulometrie, Schwermineravergesellschaftung und Tongeologie. Doctoral thesis, Rhine-Westfalian technical University of Aachen, 294 p.

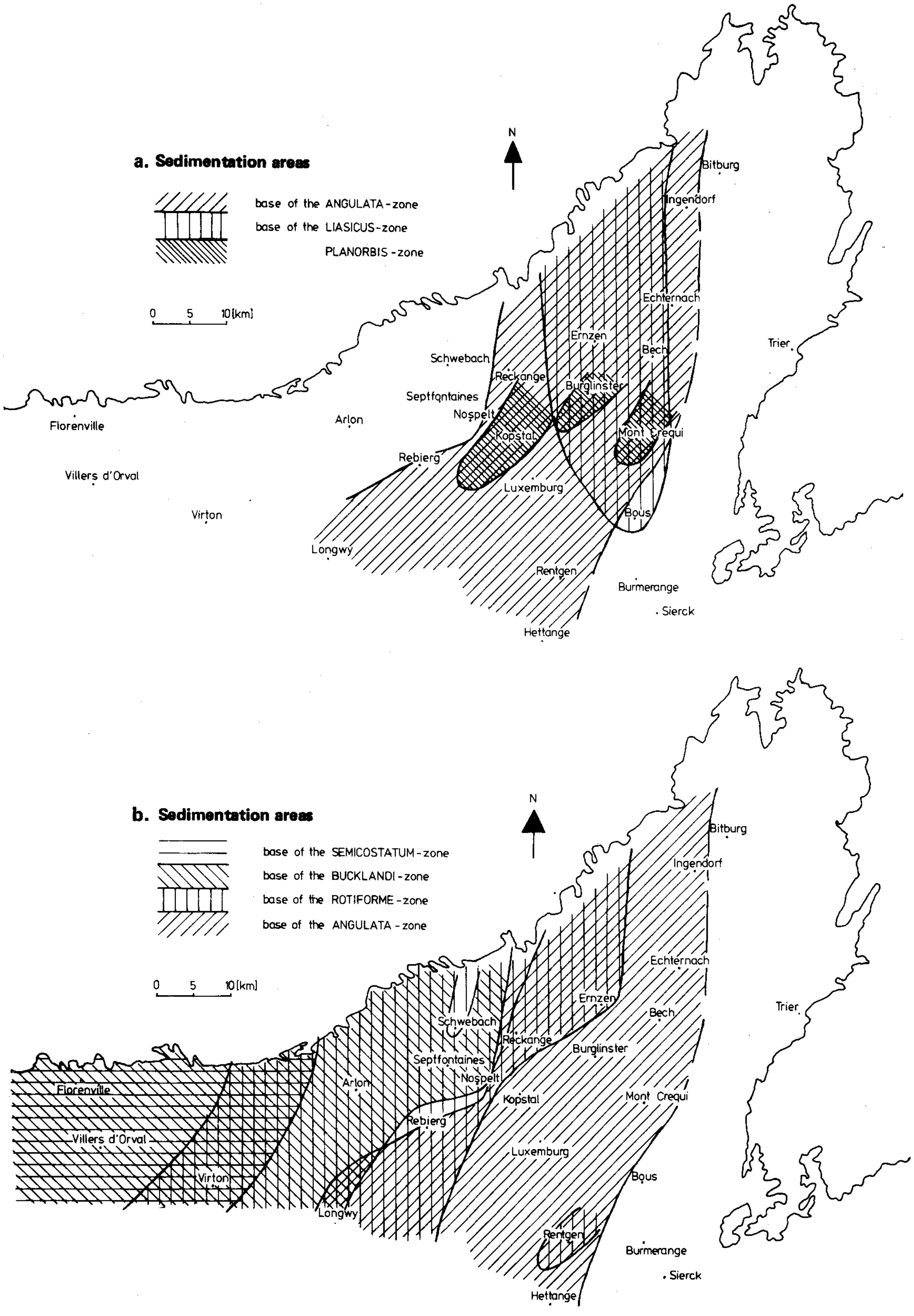

Figure 2

Paleogeographical map of the sedimentation area of the Luxemburg sandstone according to the ammonite-zones of the Hettangian (fig. 2a) and the Sinemurian (fig. 2b). Drawn after sections published by Muller (1980).

offshore bars in sand wave facies, deposited in the English Channel (Houbolt, 1968 ; Kenyon & Stride, 1970) will give an usefull clue to the methods of the investigation. But also the deviations from the recent modell has to be mentioned. Geological field work, as an exact description of the lithological features and sedimentary structures of the outcrops, is the basis of further sedimentological investigations.

The granulometric composition of the samples allows to reconstruct the hydrodynamic conditions, the development of sequences, the paths of sediment transport and the associated downcurrent fining in grain size. Investigations to the geology of clays and heavy mineral analysis give further informations to the sedimentary environment. The genesis and diagenesis of the sediment, especially of its calcareous particles, will be investigated by microscopic and x-ray analysis. The problem of the development of the carbonate content includes many open questions with regard to the environment of the Luxemburg sandstone.

It is the aim of the investigation, to assign several "standard" lithotypes, determinable from drilled cores as well as during field work, after their lithological features and sedimentary structures to definite subenvironments of the ancient offshore bar. A first outlook to these features is published in this paper.

3.2.- THE LITHOTYPES

The Luxemburg sandstone shows 6 characteristic lithotypes (fig. 4).

Lithotype 1 is a light, yellow, fine to medium grained sandstone, with a low carbonate content (< 15 o/o). Its carbonate is usually a sparitic cement. Pebbles ($\phi < 2$ cm) appear sometimes in this sandstone. The silt/clay content rarely exceeds 10 o/o of the HCl-insoluble residue.

Lithotype 2 is a light, hard and compact, fine, rarely medium grained sandstone with a high carbonate content (> 25 o/o). In most cases the carbonate is a sparitic to microsparitic cement. Bioclasts are rarely recognizable. Bioturbation is possible, above all in the fine grained sandstones with silt/clay contents between 10 and 20 o/o of the HCl-insoluble residue.

Lithotype 3 is a coquinoid, calcareous sandstone to sandy limestone. Its carbonate content comes up to 80 o/o. Bioclasts are frequent. The coarse fine-sands or medium-sands often show very well rounded pebbles up to a diameter of 10 cm. Characteristic intraformational reworking had produced pebbles of the lithotypes 1, 2 and 3. These pebbles can reach up to 20 cm in diameter. They are rounded at the edges (lithotypes 1, 2, 3), sometimes they appear well rounded (lithotypes 2, 3). Silt/clay contents up to 20 o/o of the HCl-insoluble residue have been determined. The following lithotypes, 4, 5 and 6 consider sedimentary structures, especially with regard to the inserted layers of clay and plant debris. Usually they are well developed in sandstones with a low carbonate content (< 15 o/o).

Lithotype 4 shows a large X-bedding, where bundles of sand and clay/plant debris (mm-thick) occur. This indicate varying hydrodynamic conditions, caused by tidal dominated currents.

Lithotype 5 shows dm-long, up to 3 cm thick mud drapes on *reactivation surfaces*, caused by the subordinate tidal current, separating grouped, tabular X-bedded cross sets.

Lithotype 6 is a flaser bedded, very fine grained sandstone or siltstone. This flaser bedding (Reineck & Wunderlich, 1968) is a characteristic feature of the small-scaled, x-laminated parts of the Luxemburg sandstone.

3.3.- THE LUXEMBURG SANDSTONE AT THE OUTCROP RECKANGE

This outcrop, called Reckange, is a quarry located 4 km to the west of Mersch (Luxemburg). The exposed strata comprehends the upper part of the Luxemburg sandstone, with its top and the superposed Lorraine facies (fig. 3). 50 samples have been taken and have been analyzed. The carbonate content and the granulometric composition of the HCl-insoluble particles has been determined. After its lithologic/granulometric development the outcrop Reckange could be divided into 5 sections. From 0-1 m a set of lithotype 5 is evolved, belonging to a subjacent lense of the sandstone.

The first section (1-9.3 m) starts above an erosional surface of broad lateral extent with a clay-rich layer of 2-20 cm thickness. Into this fine laminated, blue-greyish clay layer light sand lenses are inserted. The hanging lithotype 5 set contains calcareous lenses of lithotype 2. Up to 7.5 m follows an interstratification of lithotype 1 or 4 with lithotype 2. A channeled member (lithotype 3) is inserted at 3.7 m. From 7.5 to 9.3 m the lithotype 2 is more and more replaced by lithotype 3. The thickness of lithotype 1 decreases. At the top of the first section a shallow channel (lithotype 3) is developed. Here pebbles, intraformational pebbles and bioclasts are abundant. This first section

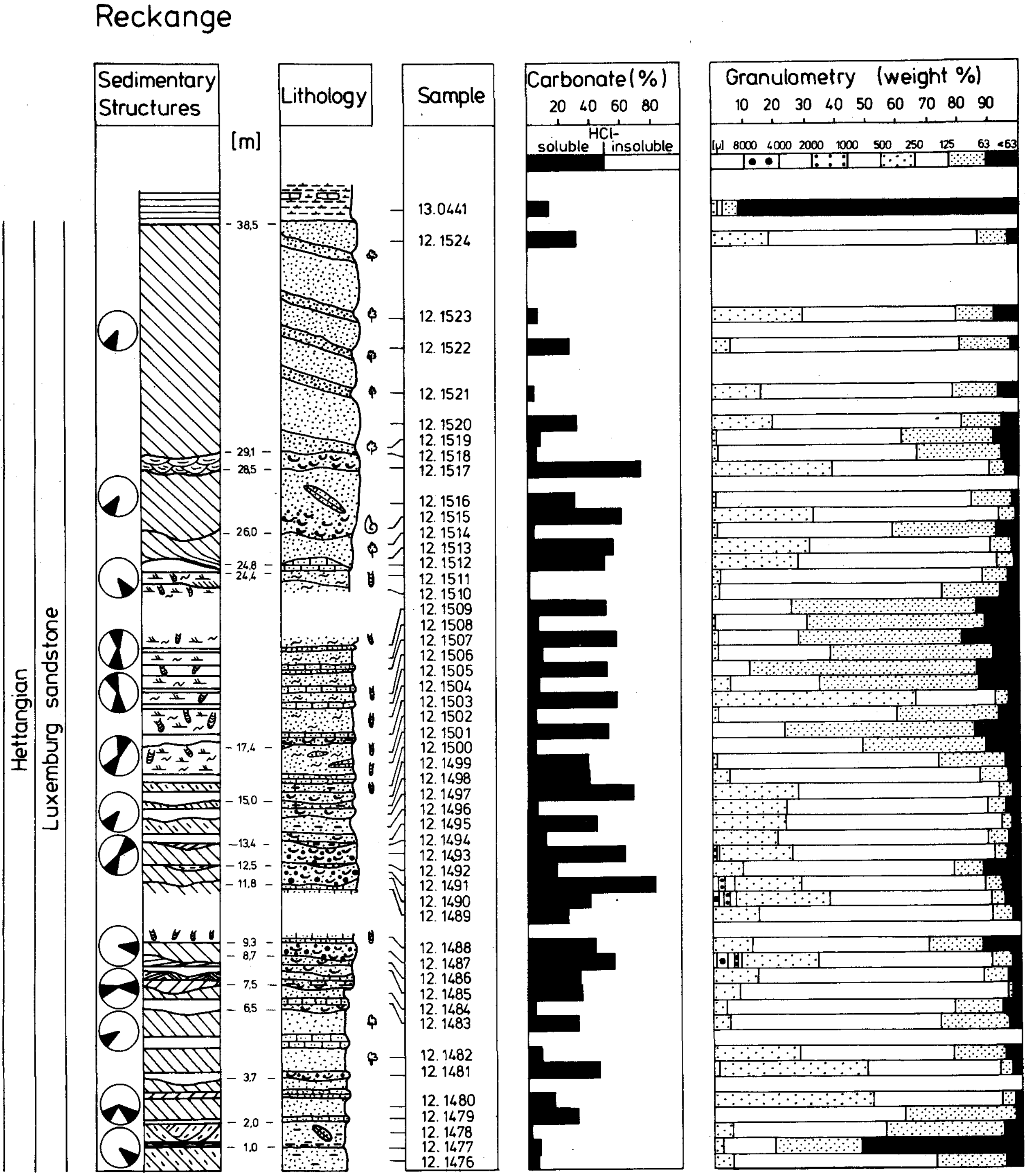

Figure 3

The outcrop Reckange. Sedimentary structures,

dip directions of cross sets, lithology, sampling points, carbonate content (weight o/o) and granulometry.

is characterized by cyclic sequences. From the basis layer (sample 1479) to sample 1481 a coarsening-up sequence, to sample 1484 a fining-up and again a coarsening-up to sample 1487 is developed.

The second section (9.3 -15 m) is characterized by rhythmic sequences, separated by erosive phases. A coarsening-up sequence starts with a bioturbated fine sand of lithotype 2 at 9.3 m. At the top of this coarsening-up sequence a shallow channel (lithotype 3) is evolved at 11.8 m. Within this channel the samples 1490-1492 show a subordinate fining-up sequence. Above the coquinoid channel lag with pebbles (sample 1490) gradationally follows a coquinoid sandstone (sample 1491). At the wave-rippled top of the channel a very fine sand (sample 1492) is preserved in a ripple trough, being not eroded by the following shallow channel. Between 12 and 15 m an interstratification of the lithotypes 3 and 5 is evolved. This part contains sediments, being accumulated by equal, high energetic conditions.

The development of the third section (15-24.8 m) shows a gradational fining-up and increasing amount of the silt/clay fraction up to more than 10 o/o. A characteristic interstratification of thicker beds of lithotype 6 with thinner beds of lithotype 2 is well developed. These "sheet-like" sandstones are fine grained, well bedded and laterally persistant. Bioturbation appears abundant in the beds of lithotype 6. This environment with its low energetic conditions is interrupted by a coquinoid, medium grained set of lithotype 3 (sample 1503). Pebbles are absent. To the top of the third section (samples 1510-1513) the fine sand fraction increases and the very fine sand fraction decreases gradational, while the medium sand fraction shows an abrupt increase.

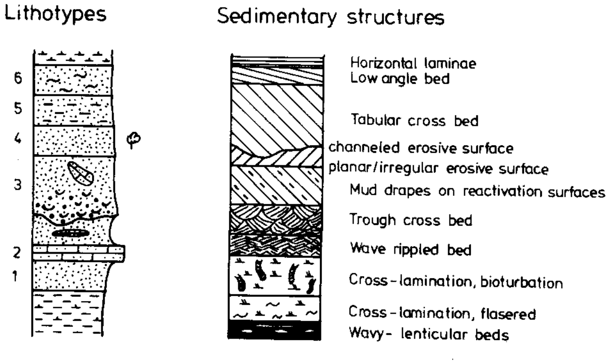

Figure 4
The lithotypes (1-6) and sedimentary structures of the Luxemburg sandstone. Drawn as a legend corresponding with fig. 3.

The fourth section (24.8-29.1 m) starts above a megarippled surface. At the lee side of the asymmetric mega-rippel a few shells have been accumulated, being covered by a thick set of lithotype 4. A channel (lithotype 3) follows at 26 m. Here calcareous lenses of lithotype 2 are orientated to the X-bedding and its reactivation surfaces. *Schlotheimia* sp. had been sampled in the channel lag. The hanging layer of this channel is a coquinoid sandstone (lithotype 3) without any pebbles. This fourth section is characterized by two rhythmic fining-up sequences in the two lower sets.

The fifth section (29.1 - 38.5 m) shows an interstratification of thinner, brown sandstones of lithotype 4 and thicker, light and mature sandstones of lithotype 2, containing a few bioclasts. Sequences are not evolved. The carbonate amount changes rhythmic with regard to the two lithotypes, just as the granulometric amount of the silt/clay fraction or veryfine/fine sand fraction. The medium sand fraction is not compared to a similar rhythmic development with regard to the two lithotypes, but shows indifferent changes in the samples of the fifth section. At 38.5 m blue marls of the Lorraine facies covers the top of the sandstone.

3.3.1.- The grain size distribution

The choosen examples of several grain size distribution curves (fig. 5) characterize the typical current and transport conditions of the Luxemburg sandstone. Depending of the intensity of the tide influenced input from the Eifel depression into the Paris Basin two grain size distribution types has been distinguished. First the shallow marine shelf sands (fig. 5a), being accumulated at lower energetic conditions than the second type, the channel sands, being formed by tide-influenced current conditions similar to those of estuarine environments (Berners *et al.*, 1983).

The shallow marine shelf sands (fig. 5a) are well to very well sorted fine sands. The best sorted grain sizes are those between 88 μ and 176 μ. The sorting deteriorates from sample 1479 to 1476 and 1478 (tab. 1). A population with rolling and sliding transport is not developed. At least 90 o/o of the grains have been transported within the saltation population. The sample 1476 and especially the sample 1478 shows between 176 μ and 250 μ a clearly worser sorted part. This indicates varying current conditions, possibly caused by tidal currents. The very poorly sorted suspension

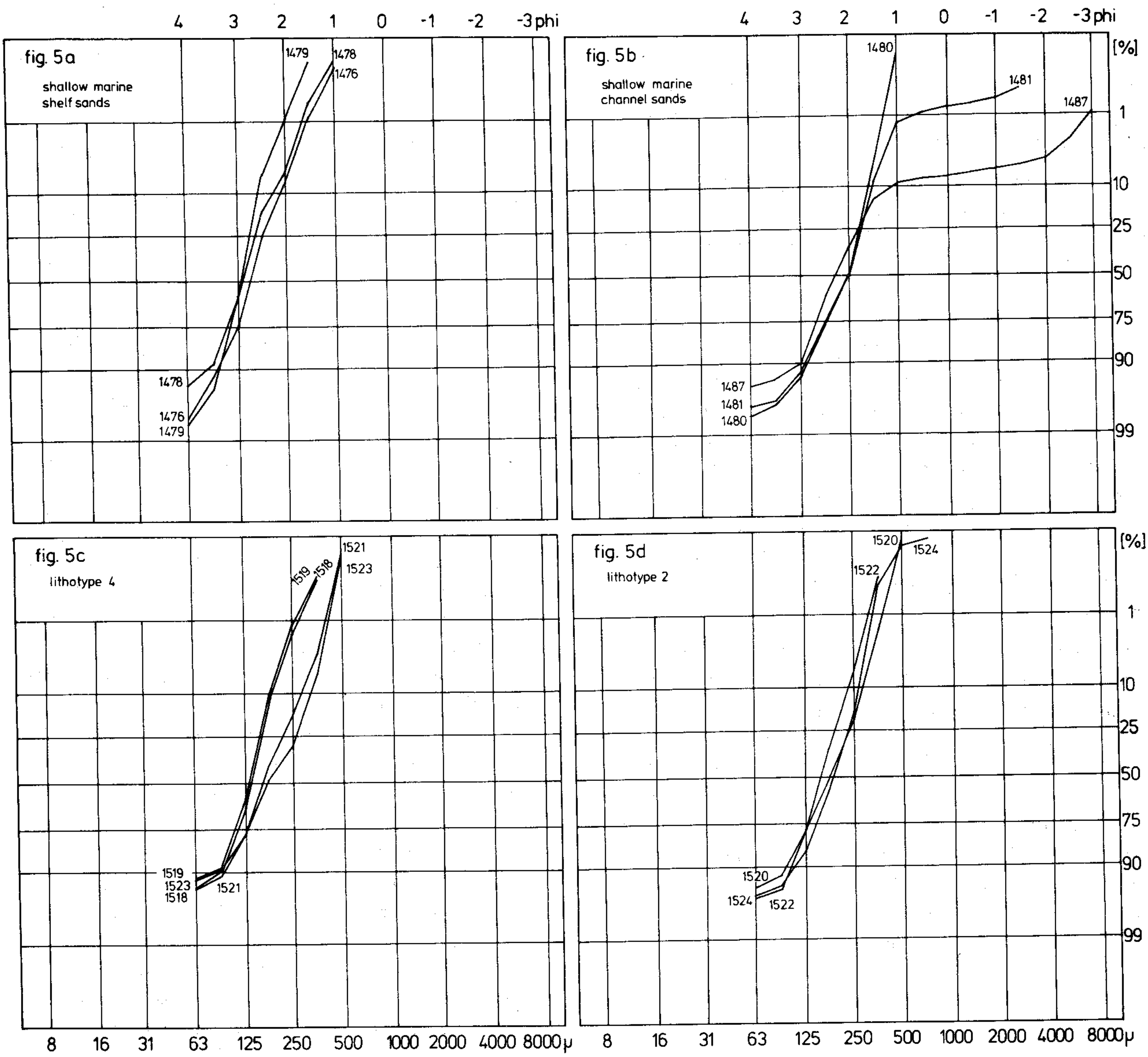

Figure 5

Grain size distribution curves of several samples of the outcrop Reckange, belonging to shallow marine shelf sands (fig. 5a, c, d) and tide influenced channel sands (fig. 5b). Neap- (lithotype 4, fig. 5c) and spring-tide sets (lithotype 2, fig. 5d) occur in a sandwave bed (tab. 1).

population (< 88 µ) amounts to 6 °/o. Similar grain size distributions of ancient shallow marine shelf sands have been published by Sindowski (1957). Grain size distribution curves from recent sediments of the "wave zone" (Visher, 1969) indicate, that the accumulation of this shallow marine sands had been controlled by tide influenced, as well as wave influenced currents and reworking.

The channel sands are well sorted fine to medium grained sands with pebbles or, on the other hand, very well sorted medium grained sands without pebbles (sample 1480). The best sorted grain sizes are those between 125 µ and 500 µ. The sorting deteriorates from sample 1480 to 1481 and 1487 (tab. 1). A rolling and sliding population is developed in sample 1481 and 1487, which shows a bimodal grain size distribution. The suspension population (< 125 µ) amounts to 9 °/o. These grain size distribution curves (fig. 5b)

Table 1

Granulometric features and typical transport conditions of several samples of the outcrop Reckange (fig. 5).

sample	median (μ)	sorting TRASK (1932)	suspension population	saltation population	rolling population
1476	150	1.20	9 %	91 %	-
1478	132	1.24	12 %	88 %	-
1479	133	1.14	7 %	93 %	-
1480	252	1.26	7 %	93 %	-
1481	250	1.30	8 %	90 %	2 %
1487	206	1.35	10 %	80 %	10 %
1520	176	1.31	8 %	92 %	-
1522	160	1.20	6 %	94 %	-
1524	190	1.25	7 %	93 %	-
1518	139	1.19	10 %	90 %	-
1519	135	1.22	12 %	88 %	-
1521	165	1.29	9 %	91 %	-
1523	177	1.40	11 %	89 %	-

represent a development from a shallow marine channel border (sample 1480) into the deeper parts of the channel (samples 1481, 1487). Similar grain size distributions from recent estuarine environments have been published by Visher (1969). These estuarine-like current conditions has been a characteristic feature for the upper parts of the offshore bars of the Luxemburg sandstone. On this very shallow shelf with usually less than 40 m depth of water (Berners, unpublished) (3), storm enhaced tidal currents eroded these channels and transported the channel-fill sediments (Brenner & Davies, 1973).

The grain size distribution curves of the samples from section 5 of the outcrop Reckange (fig. 5c, 5d) are similar to those of the shallow marine shelf sands (fig. 5a). With regard to lithotype 2 (fig. 5d), the lithotype 4 (fig. 5c) has a usually higher amount of the suspension population. The rolling and sliding population is absent in both lithotypes.

The granulometry of these samples (fig. 3) indicates for lithotype 4 a higher amount in the silt/clay fraction. Its sand fraction comes up to 91-94 o/o, at which the very fine sand fraction amounts to 15-29 o/o. The sand fraction of the lithotype 2 is coarser and comes up to 95-97 o/o, at which the very fine sand fraction amounts to 11-14 o/o. The typical lithologic interstratification (fig. 3), the unidirectional sediment transport to the SW and the usually lack of erosional surfaces indicates a mega - rippel of the sand wave type after Nio (1976) for the upper section at Reckange. The lithologic interstratification represents bundle sequences according to the different energetic conditions, producing lithotype 4 during neap-tides, lithotype 2 during spring tides. The medium sand fraction may be influenced by episodic storm events, superposing the neap-spring tide sedimentation cycles.

3.3.2.- Carbonate content

The genesis of the interstratification of the high-carbonatic lithotypes 2 or 3 with the low-carbonatic lithotypes 1, 4, 5 or 6 remains an open question (fig. 3). The following statements may give answers to parts of the genetic and diagenetic development of the carbonate content. The macro- and microscopic recognizable bioclasts will have been the source of the carbonate content (Preugschat, unpublished (1)) (Berners, unpublished) (3). Sedimentary structures, hardgrounds, bioturbation and intraformational pebbles give decisive indications to a synsedimentary/early diagenetic lithification of the sandstone.

In lithotype 3 the synsedimentary bioclasts usually are macroscopic recognizable. Here the intraformational pebbles, orientated to the X-bedding surfaces, have a really different carbonate content compared to them of the surrounding sediment. Its amount can be higher (pebbles of lithotype 2, 3) or lower (pebbles of lithotype 1, 4).

The fine grained lithotype 2 has rarely macroscopic recognizable bioclasts. It is not obvious, to interpret the carbonate content being of bioclastic origin. Further microscopic investigations would be necessary. The third section at Reckange shows, that within the interstratification of the lithotypes 2 and 6 no granulometric variation appears in accordance to the rhythmic variation in the carbonate content from lower 10 o/o up to more than 30 o/o. Here the development of synsedimentary hardgrounds, formed during stages of reduced sedimentation, may be the reason for the high carbonate contents of the bioturbated lithotype 2 sediments.

Nevertheless different results of microscopic investigations to a high carbonatic (52 o/o) sample (lithotype 2) and its hanging layer of a low carbonatic (8 o/o) lithotype 1, both with an equal quartz grain size distribution, support the opinion of a synsedimentary received carbonate content even for some lithotype 2 sediments (Berners, unpublished) (3). The lithotype 1 sample has a higher packing density of the quartz grains and its porosity is lower than 3 o/o. This sandstone is lithified by a sparitic cement and no bioclasts have been recognizable. The size of the carbonatic crystals is usually lower than the size of the quartz crystals. The compared sample of lithotype 2 shows bioclasts, which are greater than the quartz grains. In most cases it is difficult to identify the bioclasts, because their primary structure has been destroyed by sparitic overgrowing. The bioclasts and quartz grains are cemented by two, often more cement generations. The porosity is lower than 1 °/o. The quartz grains show marginal replacements by calcite, but also not attacked parts are recognizable. A replacement up to 50 °/o of the quartz grains by calcite could not be proved.

The diagenetically received carbonate cement is usually a microsparite or sparite. Early diagenetic fibrous cement caused a fast lithification. Block cement of several stages closes the remaining open pores. Late diagenetic solution of calcite by vadose water is possible. It produces loose sands as solution residue. On the other hand calc-sinter appears at sources. As seen above, the porosity even in the low-carbonatic lithotypes usually is very low (< 5 °/o). A remarkable break within the amount of the carbonate content appears between 15 °/o and 30 °/o (fig. 3). The lithotypes 1, 4, 5 and 6, lithified by a diagenetically received cement, come up to 15 °/o, the carbonate types 2 and 3 to more than 30 °/o. It is obvious by the previous statements, that the variations in the carbonate content are the product of sedimentary as well as diagenetic processes.

3.4.- SEDIMENTARY STRUCTURES

Current induced sedimentary structures are the dominant type in the Luxemburg sandstone environment. They are produced by tidal currents or wave (storm) induced currents, which also are able to form asymmetrical internal structures (Newton, 1968). Typical symmetric "chevron" - structures (Boersma, unpublished) (6), developed in wave-generated oscillation ripples, have rarely been observed (fig. 3, 7.5 m). The palaeocurrent patterns (fig. 8) clearly indicate a dominant direction (S/SW), according to the ordinate tidal current. The strength of the bidirectional tidal currents differs and the subordinate current (N/NE) in most cases is not able to produce preservable, reversal, up-slope migrating ripples. This current often forms secondary structures as reactivation surfaces. Obvious are these features in the sets of lithotype 5, with mud drapes and calcareous lenses associated with the reactivation surfaces.

After McKee & Weir (1953) x-lamination and X-bedding has been differentiated (fig. 4), according to small-scale and large-scale structures (Allen, 1963). The large-sclae structures or megarippels are called "sand wave", if the height of the rippel comes up to more than 8 m (Nio, 1976). Further differentiations separate tabular and trough cross sets, low angle bedding and parallel lamination (fig. 4).

The features of the sedimentary structures are usually not recognizable in the lithotypes 1 and 2. According to the well developed cross sets in the lithotypes 3, 4, 5 and 6 it is likely, that the lithotypes 1 and 2 also are cross stratified members.

Because of the frequently interrupted accumulation of the offshore bar sands by strong and persistant erosive phases the observed cross sets often cannot be identified by the nomenclature after Allen (1963). Sometimes recognizable are the solitary large-scale sets *Alpha, Beta, Gamma, Epsilon,* the small-scale grouped sets *Kappa, Lambda, Nu* and the large-scale grouped sets *Omikron* and *Pi.* In addition, the *Omikron* cross sets, according to lithotype 4, show layers of clay and plant debris inserted in the cross sets.

In most cases the boundaries of the sets are erosive. Low angle erosive surfaces of broad lateral extent, low relief and lacking deep channeling contrast with those formed in estuaries, barrier inlets or rivers. Erosive surfaces, associated with an open marine in situ fauna (hardgrounds, fig. 10, facies 6), reflect a complete cessation of sand transport.

Three forms of erosive surfaces may be differentiated after Anderton (1976) (fig. 6). The channeled erosive surfaces frequently show a channel lag consisting of pebbles and large bioclasts. Usually the slopes of the shallow channels dip with less than 10°. Steeper dipping channels (max. 15°) are developed only in the southern Eifel and the NE-Gutland. The irregular erosive surfaces dip with very low angles (less than 5°), rarely up to 10°. The low relief of these surfaces comes up to a few decimeters. The planar erosive surfaces are laterally persis-

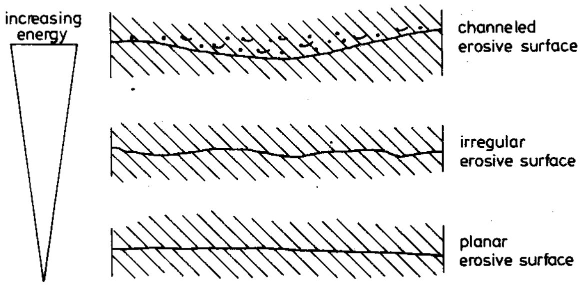

Figure 6
Types of erosive lower boundaries of the sets in the Luxemburg sandstone.

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(6) BOERSMA, J.R., 1970. Distinguishing features of wave-ripple cross-stratification and morphology. Doctoral thesis, University of Utrecht, 65 p.

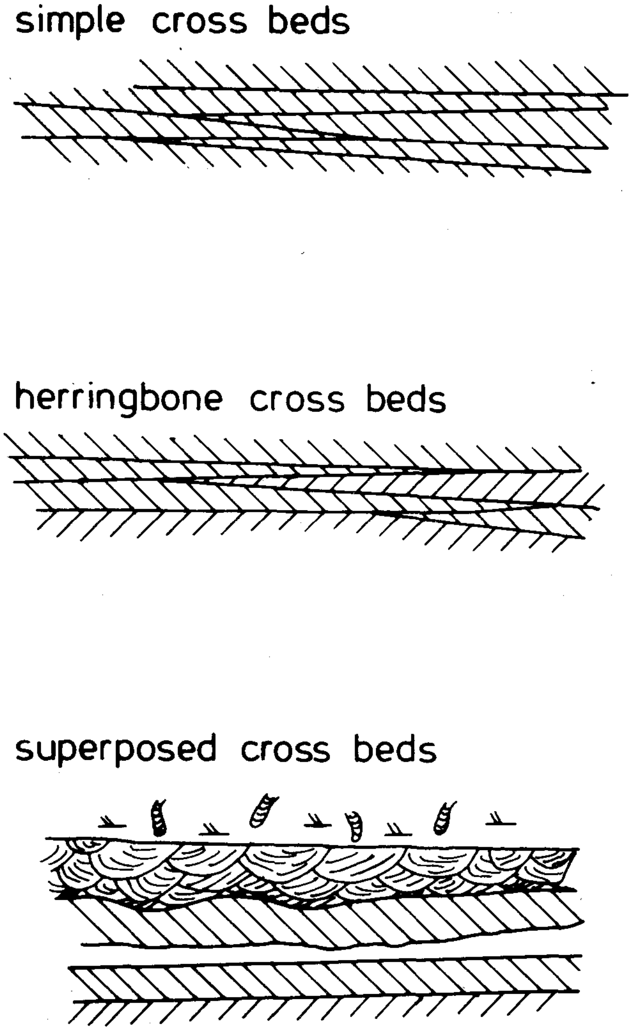

Figure 7
Types of grouped sets in the Luxemburg sandstone. The superposed beds are the main type, where simple cross beds (grouped sets after Allen, 1963) and herringbone beds are inserted.

tant and dip with angles less than 5^{o}. The relief amounts to a few centimeters.

Because of the number and strength of the erosive contacts it is necessary to revise the nomenclature of the grouped sets with regard to Allen (1963). The main type of grouped sets is called superposed set (fig. 7). They are limited by the Lorraine facies, even by recurrences of this facies being a few centimeters thick. The clay/silt amount of these recurrences has to come up to more than 50 $^{o}/_{o}$ of the HCl-insoluble particles. The superposed sets build up a complete offshore sand lense (fig. 3, 1-38,5 m). The strong erosive phases are able to combine several subenvironments and their accompanied sedimentary structures. Cross stratified, parallel laminated, wave rippled as well as sections without any recognizable internal structures (lithotypes 1 and 2) are included.

Inserted into these superposed sets are the simple sets and herringbone sets (fig. 7). The simple sets agree with the grouped sets after Allen (1963). They comprehend cross sets of one type (*Omikron, Pi* etc.) and indicate unidirectional sediment transport. The herringbone sets are grouped, large-scaled and tabular bedded. The erosional surfaces separate opposite dipping sets.

At Reckange (fig. 3), between 1 and 38,5 m, a superposed set is developed. The basal silty clay layer has a broad lateral extent. Small-scale ripples (*Kappa ;* Allen, 1963) are developed and sandlenses are inserted (lenticular-bedding ; Reineck & Wunderlich, 1968). Up to 2 m a simple *Omikron*-set (Allen, 1963) appears, showing mud drapes and calcareous lenses at the reactivation surfaces. Two ripples, with sediment transport to SE and SW, are recognizable. Between 2 and 7.5 m an interstratification of "non-structured" lithotype 2 sediments and X-bedded sandstones is developed. Planar erosive surfaces separate the sets. At 3.7 m and 6.6 m the erosive surfaces are irregular. A herringbone set is preserved at 7.5 m. Above a wave rippled sandstone a low angle to parallel laminated sandstone follows. A *Gamma*-set (Allen, 1963), with a channeled lower boundary and tabular cross sets is developed at 8.7 m. Another channel of this type appears at 11.5 m. Up to 13.4 m a herringbone set is preserved. An interstratification of "non-structured" lithotype 2 sediments and *Omikron*-sets (Allen, 1963) follows. Its basal surfaces are irregular erosive and the reactivation surfaces contain mud drapes.

In the third section at Reckange (fig. 3) "sheet-like" sandstones are abundant, usually with small-scale structures as *Kappa*-sets (Allen, 1963), flasered beds (Reineck & Wunderlich, 1968), laminated beds, low angle beds as well as bioturbation. The inserted beds of lithotype 2 show no internal structures, except of bioturbation. The wavy tops seem to be small-scale rippled. At 17.4 m a storm induced layer of the lithotype 3 is inserted, having an irregular lower boundary and a gradational transition to its hanging layer. The asymmetric rippled surface at 24.8 m (ripple height 30 cm) is covered by a non-erosive *Alpha*-set (Allen, 1963). At 26 m a *Gamma*-set (Allen, 1963) with a channeled erosive lower boundary is developed. Calcareous lenses are orientated to the cross sets. Between 28.5 and 29.1 m the only trough cross bed at Reckange occurs (*Pi*-set ; Allen, 1963).

In all sets of the fifth section at Reckange (fig. 3) the same direction of sediment transport is developed. Broad and strong erosive surfaces have not been recognized. Reactivation surfaces sometimes appear. The foresets dip with 16° to 34° to the SW. The height of this sand wave is at minimum 9 m.

4.- DEVELOPMENT OF THE SEDIMENTARY ENVIRONMENT OF THE LUXEMBURG SANDSTONE

4.1.- PALAEO CURRENT DIRECTIONS

The possibility to measure dip directions of cross sets is submitted in individual outcrops to some accidental and subjective influences. Because of the lithologic maturity and homogenous texture, especially in the lithotype 1 and 2 sets, internal sedimentary structures often could not be recognized. Therefore the measurements of an individual outcrop should not be plotted into diagrams as a percentage according to the number of measurements. All the different dip directions should be drawn as arrows of equal length (fig. 3). Otherwise accidental and local, not genetically caused maxima are established in the rose diagrams of individual outcrops. If the measurements of the several outcrops of an area, like the NE-Gutland etc., are summarized, the large number of measurements as well as the large number of regional distributed measuring points prevents local influences.

The palaeo current directions of the several investigated areas (tab. 2) are plotted in fig. 8. In the region of Gaume (Belgium) beside own measurements those published by Monteyne (1960b) have been considered.

The sediment transport from north through the Eifel-depression into the Paris Basin is caused by the dominant, ordinate tidal current, which overwhelmes in every rose diagram (fig. 8) the subordinate tidal current. Reactivation surfaces, formed by the weaker reversal tidal current, are more frequent than its cross sets.

From the southern Eifel through the NE- and W-Gutland to the Gaume the ordinate tidal current shifts longshore from a southern direction to a western one. In the S-Eifel two maxima (175g/215g) are developed, which shift to 215g/255g in NE- and W-Gutland and to 225g/270g in the Gaume. These two maxima, of equal size in the S-Eifel, possibly originates in the internal structure of an offshore bar, at which the sand body elongation is situated between these maxima.

Table 2
Number of current direction measurements in different parts of the studied area.

	area	measurements
1	S-Eifel	220
2	NE-Gutland	194
3	E-Gutland	284
4	SE-Gutland	224
5	W-Gutland	188
6	Gaume	240

The SE-Gutland shows heterogenous and different current directions. Beside the tide influenced currents (205g/245g) and their subordinate reversals another well developed direction to the NW (325g) appears. This third direction can be recognized in a weaker form in E-Gutland (325g), W-Gutland (345g) and the Gaume (345g).

The E-Gutland represents a transition zone between the S-Eifel and NE-Gutland with its tide dominated currents, advancing through the Eifel-depression, and the SE-Gutland, which is affected by shallow marine, probably wave induced currents. This current to the NW follows the direction of the Liassic transgression up to the Ardennan continent. Local affects, according to the sill of Sierck, and regional affects, as the opening to the broad and shallow marine shelf of SW-Germany and the Lorraine, may be the origin of the strong development of this current direction in the SE-Gutland.

4.2.- SUBENVIRONMENTS OF THE ANCIENT OFFSHORE SAND BAR

Lithological and sedimentary features as high textural and mineralogical maturity as well as laterally extensive, low relief erosion surfaces and the absence of deep channeling give decisive indications to a shallow marine environment. Also the autochtonous/allochthonous fauna of the Lorraine facies and the Luxemburg

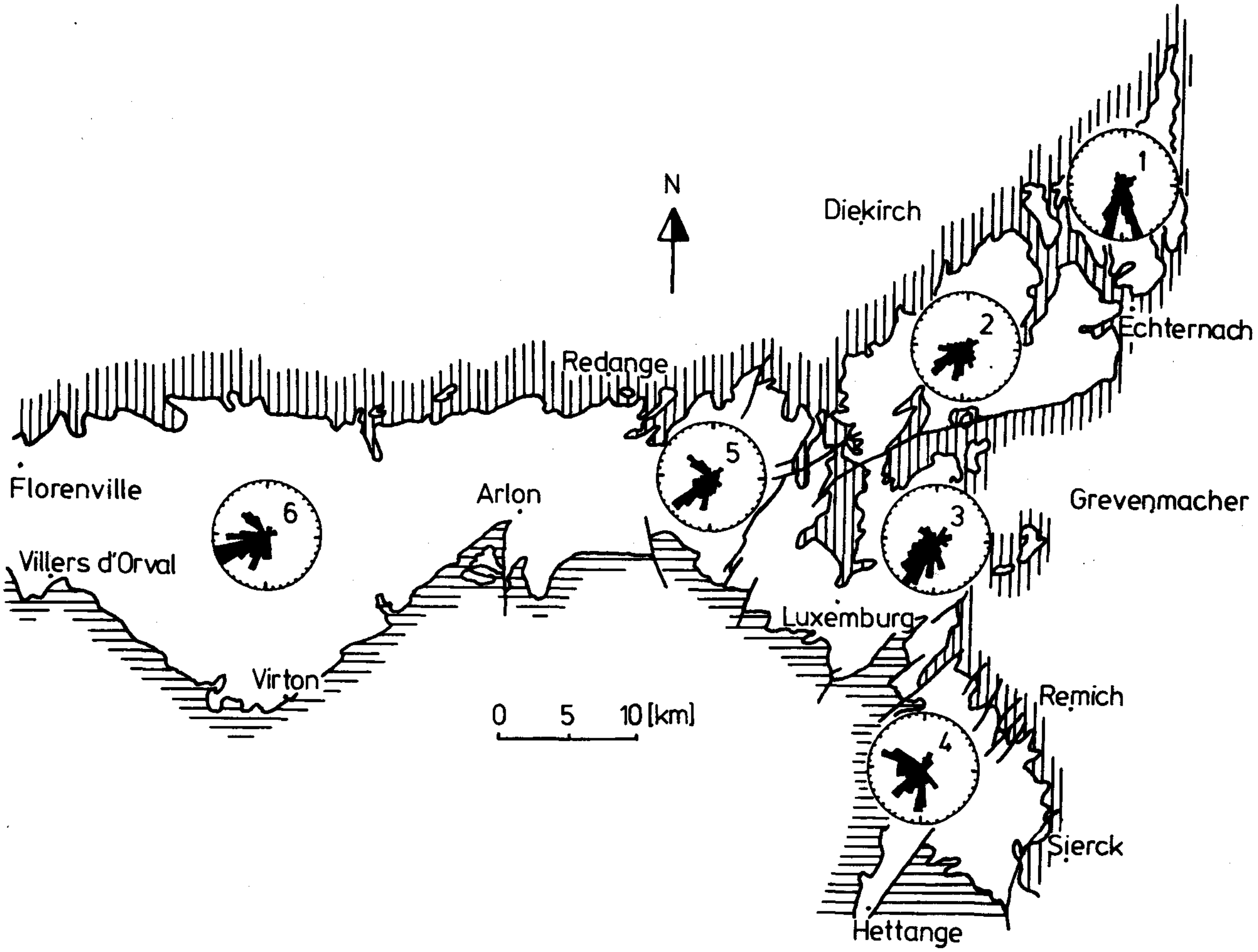

Figure 8
Palaeocurrent directions according to the studied areas S-Eifel (1), NE-Gutland (2), E-Gutland (3), SE-Gutland (4), W-Gutland (5) and the Gaume (6). The radius of the rose diagrams correspond to 50 measurements (tab. 2).

sandstone facies demands a shallow marine, subtidal environment. Algae structures, characteristic to inter- or supra-tidal flats, never could be recognized as an autochthonous part of the sediment. Only reworked coated grains are frequent in some subenvironments. A development of the sand lenses up to the inter- or supra-tidal environment may be possible. But these tidal flats will rarely be preservable, because of the high energetic, transgressive reworking and redepositional processes.

The palaeogeographic situation of the Lower Lias of western Europe as well as faunistic features support the existance of a marine channel in the Eifel-depression (Muller, 1980 ; Hendriks, unpublished (5) ; Ziegler, 1982). Within the Eifel-depression high energetic conditions base on estuarine-like tidal currents. As this channel gets broad by the opening to the Paris Basin, a decrease in the tide influenced hydrodynamic conditions is obvious by the downcurrent fining of the grain sizes (Monteyne, 1960a ; Berners, unpublished) (3).

From the S-Eifel to the SW the number of pebbly channel lags and beds of lithotype 1, 4 and 5 decreases, while the number of beds of lithotype 2 and 3 increases.

The nomenclature of the several subenvironments follows a paper published by Nio (1976). 6 subenvironments can be separated, which appear in different areas more or less frequent and with varying thicknesses. Figures 9 and 10 show the development of the subenvironments of the offshore bars.

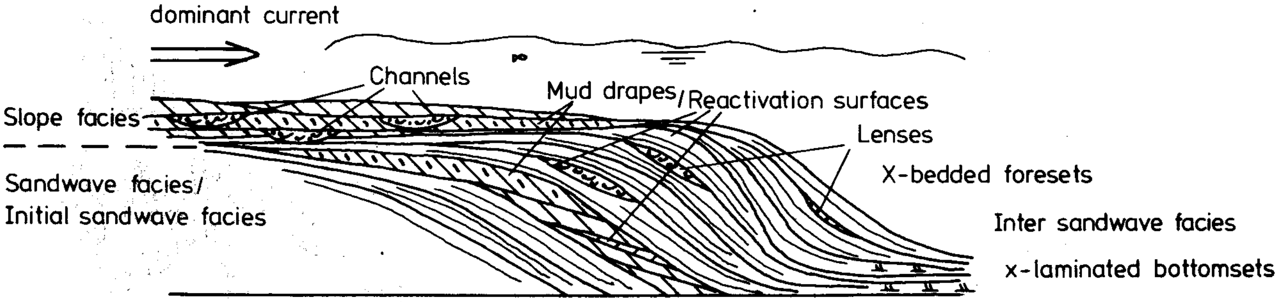

Figure 9

Generalized section through a tide influenced sand bar and its typical sedimentary structures. The shallowing of the sea bottom is remarkable and takes place by a lateral and vertical development from the inter sandwave facies to the slope facies.

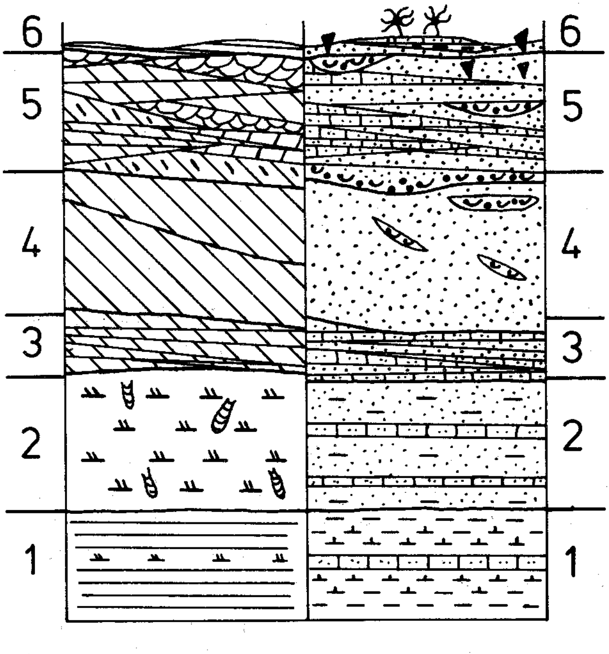

Figure 10

Generalized vertical section through the subenvironments of the offshore bar of the Luxemburg sandstone, considering lithological features and sedimentary structures (s. fig. 3). These subenvironments are : shelf mud facies (1), intersandwave facies (2), initial sandwave facies (3), sandwave facies (4), slope facies (5) and abandonment facies (6), after Nio (1976).

The shelf mud facies (fig. 10, 1) comprehends the Lorraine facies with blue, clayey marls and bioclastic limestones. These sediments show parallel laminated, sometimes X-laminated beds. The limestones partly have erosive lower boundaries. In most cases gradational transitions between the clays, marls and limestones are developed.

The inter sandwave facies (fig. 10, 2) comprises bioturbated silts and silty sandstones of the lithotype 6, as well as bioclastic sandy limestones (sheet sands) of the lithotype 2. They occur inserted between the interfingering sand lenses and as a transitional zone of the shelf mud facies to the initial sandwave facies (fig. 9). The sedimentary structures are usually small-scale rippled, flasered or wavy laminated beds.

The initial sandwave facies (fig. 10, 3) consists of fine to medium grained sandstones of the lithotypes 1, 4 and 5, occasionally with pebbles. The lithotypes 2 and 3 rarely occur (fig. 9). The high energetic conditions produce X-bedded sets, with tabular, low angle foresets (< 20°). Laterally persistant erosive surfaces separate the cross sets, which have been formed by the dominant tidal current. But also those of the weaker, reversal current are sometimes preserved.

The sandwave facies (fig. 10, 4) is characterized by tabular cross bedded sandstones, fine to medium grained with occasionally pebbles orientated in the unidirectional cross sets (fig. 3, at 29.1 to 38.5 m).

Internal erosional surfaces as reactivation surfaces are developed, with calcareous lenses according to the modification by the subordinate current (fig. 9). The lithotypes 1 and 4 are abundant. Partly tidal bundles occur.

The slope facies (fig. 10, 5) consists of an interstratification of the lithotypes 1, 2 and 3, partly with ooids. Occasionally the lithotypes 4 and 5 occurs (fig. 3, at 1 to 29.1 m). The tabular or trough cross bedded sandstones are separated by large-scale, low angle erosive surfaces. The fore sets of the megaripples mainly dip down the slope (ordinate tidal current, thicker beds), more rarely up the slope (subordinate current, thinner beds) (fig. 9). The hydrodynamic conditions are more varying than in the previous subenvironments, but the tidal current to the SW is still dominant (except of SE-Gutland). In this very shallow subenvironment of a few meters water depth local effects as the morphology of the sand bars or wave (storm) induced currents are more important than in the previous subenvironments. In protected areas (fig. 3, at 15 to 24.4 m) a slow and very fine grained sedimentation took place. Bioturbation, consisting of vertical *(Rhizocorallium, Diplocraterion)* or horizontal burrows, trace fossils as well as small-scale structures are frequent. The flasered, very fine sands are well bedded with a broad lateral extent without lensing. Sheet sands with erosive lower boundaries are inserted. This subfacies could have lateral and vertical transitions to the inter sandwave facies.

The abandonment facies (fig. 10, 6) is developed at the top of the offshore bar. The sedimentation is reduced or is lacking. Its a thin, in most cases fossiliferous bed (1 m), with an autochthonous fauna of *Pinna* sp., especially in beds of the lithotype 1, or sessile echinoderms, corals, forams, algae and lamellibranchs, settling at beds of the lithotypes 2 or 3 and forming a hardground.

The thickness of the beds is increasing from those of the shelf mud facies up to those of the sandwave facies. Then it decreases very fast and in the abandonment facies sedimentation starves. A dominant coarsening -up sequence is developed from the shelf mud facies to the slope facies. Here, as well as in the initial sandwave facies fining-up sequences are inserted. In these subenvironments the strong and varying current conditions and frequent erosive phases often prevents well developed sequences.

The initial sandwave facies and the sandwave facies are more frequent in the S-Eifel and NE-Gutland than in the other areas, where the slope facies is the dominant type. The inter sandwave facies and the abandonment facies are irregularly inserted.

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