FACIES	15	1-34	Taf. 1-9	9 Abb.	1 Tab.	ERLANGEN 1986

Trends in the Development and Cyclic Patterns of Middle and Upper Devonian Buildups

Entwicklungstendenzen und Zyklizität bei mittel- und oberdevonischen Riffen

Jindrich Hladil, Brno

KEYWORDS: MICROFACIES - VERTICAL DEVELOPMENT - PALEOENVIRONMENT - CYCLIC PATTERNS - RATE OF SEDIMENTATION - MIDDLE TO UPPER DEVONIAN

CONTENT

SUMMARY

A comprehensive review of Middle and Upper Devonian reefs, based on about 350 papers describing the reef development within 44 areas all over the world, resulted in the recognition of four reef megacycles (Upper Eifelian; Givetian; Uppermost Givetian to Frasnian; Upper Frasnian to Lower Famennian). These megacycles are characterized by the occurrence of typical reef types and by characteristic microfacies associations. Twelve microfacies associations can be distinguished using lithological, paleontological and microfacies criteria; each microfacies association includes several standard microfacies types.

The evolution of the Middle and Upper Devonian buildups is illustrated by a sequence of nine stages (Fig. 2): Semilagoonal stage with pioneer bentic communities; Stage with coral and brachiopod banks; Stage with *Amphipora* banks and flat mud mounds with stromatoporoids; Stage with stromatoporoid-coral banks occurring within scattered patch reefs; Lagoonal stages, generally regressive; Stage with shoals or barrier reefs (including a fore-reef development as well as reef margins with a back-reef facies); Reef cap stage indicating the end of reef growth; Stage of drowned reef surfaces with carbonate sands and gravels; Stage characterized by the beginning of a non-reefal sedimentation (mainly nodular limestones).

Differences between Devonian and recent reefs include the frequency of the standard microfacies types (Fig. 5) as well as different tectonic settings of the reefs (about 80% of the reefs were formed in the area of rapidly subsiding platforms or quasiplatform blocks within miogeosynclines; the angle of the platform slopes was smaller than in recent examples).

1 INTRODUCTION

The general pattern of the sedimentation of Middle and Upper Devonian carbonates has been discussed by many authors (BURCHETTE 1981, DVORAK 1980, HOFFMAN & NARKIEWICZ 1977, HOUSE 1974, KREBS 1971, 1974, LONGMAN 1981, TSIEN 1981, WILSON 1975, ZAGORA 1983). A comprehensive review of the facies types on a global scale, however, appears to be missing. The author has tried to fill this gap with a study carried out during petroleum prospecting (HLADIL

Address: Dr. J. Hladil, Ustredni ustav geologicky, Leitnerova 22, CSSR 60200 Brno

	Thickness of the Carbonate Build-up (m)	Stratigraphic Range	Time of Sedimentation in Mil. Years	Sedimentation in Meters per 1 Mil. Years	STANDARD MICROFACIES																								MICROFACIES ASSOCIATION											
					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	A	B	C	D	E	F	G	H	I	J	K	L
1. Leduc, Stettler, Redwater	180	M. to U. Givetian?	4	45					•	•	○	●	○	●	●	•	•			○	•		○	○	•	○	⬤		•	•	●	●	⬤	•					•	•
2. Swan Hills	50	U. Givet. to L. Fras.	4	13					●	●	⬤	⬤	○	●	•	•	●		•	●	•	•	○	●		●			•	•	•	●	○	•	●	•	•	●	○	•
3. Miette	400	U. Giv. to U. Fras.?	8	50	•		•		●	•	⬤	●	•	•	⬤	○	○							○				•	•	●	•	●	●	•	○	●	•		•	
4. Ancient Wall	450	Givetian to U. Fras.?	11	41			•	•	•	●	○	•	○	•	⬤	⬤	•			●	•									•				○	○	•	•	⬤	●	
5. Northwestern Territories	250	U. Eifel. to L. Fras.	8.5	29	•	•	•		•	•	●	●	⬤	○	●	●		•												○	●	•	⬤	•		●	●			
6. Southwestern Alaska	1000	Eifel. to L. Fras.	10	100		•	•	•	•		⬤		○	●		○	○			●	•	•	•	⬤					•	•	●	●	○	•	●			●	•	●
7. Pacific Northwest	200	U. Eifel. to Givet.	6	33							○	•	•	●	○	⬤	●			○		•	•	○					•	•	•	●	⬤	•					○	
8. Nevada	300	U. Eifel. to Frasnian	15	20						•	⬤	•	•	•	⬤	●	•		○	○	•	•	•	•	•	•	●	•	⬤			•	○	•	•				○	
9. Williston Basin	100	Givet. to Frasnian	11	9					○		○	●	○	•	•	•	•	•	•	○	○	•	●	•	●	○	⬤	○	⬤	•			●	•					○	
10. Eastern USA	40	Eifelian to Givet.	10	4							●	•	⬤	•	•	•	•	●					○				●		●	⬤	•	•	•	•					●	
11. Cantabrian Mountains, Spain	360	U.Givet. to L. Fras.	5	72		•	●		•	●	○			○	●	⬤	•		●	•	•	•							•	•	•	•	⬤		●	•	•		○	○
12. Montagne Noire, France	200	Givet. to L. Famen.	14	14	○	•	○	•	●	•	•	●	⬤	•	•	•	•			•	•	•								●	•	•	●		•		•	•	•	●
13. Southwestern England	500	Eifel. to Frasnian	15	33	•	•	•			•	○	○	⬤	●	•	●	•			•	•	•	○	•	•	•	•	•	•	•	•	●	○	•	•			●	●	●
14. Bretagne	150	Eifel. to Givetian	10	15		•	•	•	●	•	•	●	⬤	●	•	•	•	○		●	•		•	•					●	⬤	•	•	●	•			•	•	○	○
15. North Sea	100	Givetian	4	25						•	○	○	•	●	•		•	•	•	●	•	○	○	•		•	⬤	●	⬤	•	•	●	○	•					○	●
16. Boulonais, France	350	Givet. to Frasnian	11	32	•	○	•	•	●		○	⬤	○	●	•					•	•		○	○		•			●	●	•	•	•	•			•		•	●
17. Basin of Dinant	800	Eifel. to M. Fras.	13	62	•	•	●		●	•	⬤	○	⬤	●	•	•	•	•		•	•	●	○	•	•	•	•	•	•	●	●	●	●	•	⬤	•	•	•	•	●
18. Eifel, Germany	600	Eifel. to M. Fras.	13	46	•	•	•	•	○	•	○	○	●	●	•	•	•			•			○	•					•	•	•	●	○		○	●				○
19. Rhenish Schiefergebirge	1300	Eifel. to M. Fras.	13	100	•		●	•	•	●	⬤	○	○	●	•	•	•		•	●	•	●	○	●	•	•		•	●	•	•	●	○	•	●	•		•	●	●
20. Harz	600	Givet. to Famen.	19	32	•	●	•	●	○	○	○	●	●	•	○	⬤	•	•		•			○	○		•			•	•	•	•	●	•	○	○	●	●	●	●
21. Moravia	1600	Eifel. to L. Famen.	19	84	•	•	•	•	●	•	⬤	○	⬤	●	•	•	•	•		•	•	●	○	•	•	•	•	•	•	●	●	○	●	•	○	•	•	•	•	●
22. Thuringia	30	Eifel. to Famen.	26	1.1	•	●	⬤	•			•	○	○	●				•		•									•	•			•				○		●	⬤
23. Westsudetic region	20	Eifel. to Famen.	26	0.8			○		•		•	•	⬤	•						●									•	•		•	•				●		⬤	⬤
24. Pomerania, Poland	400	U. Eifel. to Fras.	15	27			•		•		⬤	•	○	●	●	•	•						○	○		●	•		●	•	●	●	⬤	•	•	•			•	●
25. Krakow region	500	Eifel. to Fras.	16	31	•	●	•		•	•	○	○	⬤	●	•	•	•			●	•	•	○	•	•	•	●	•	•	•	●	●	○	○	●	•		●	○	○
26. Holy Cross Mts., Poland	600	Givet. to L. Famen.	13	46	•	•	•	•	•	●	⬤	●	⬤	●	•	•	●		•	●	●	•	●	○	•	•		●	•	●	●	○	○	•	○	●	•	•	•	○
27. aulacogen of Lublin	600	Eifel. to Fras.	15	40			•		●	○	●	⬤	●	•	•		•			○	○	•							•	•	•	⬤	○		●				●	○
28. Northern Hungary, Slowakia	800	Eifel to Famennian	25	32							○	○	⬤	●	•	•	•						•	○	•	•			•	○	•	•	●	•	•			○	○	○
29. Carnic Alps	150	Eifel. to Famennian	21	7	●	○	⬤	○	•	•		●	○	•	•	●	•	•					•			•			•	•	•	•	○	•		○	○		•	⬤
30. Serbia, Yougoslavia	100	Givet. to Frasnian	11	9		•	⬤	•			⬤	○	•	•										•						•		•	⬤				●		•	⬤
31. Bulgaria	?	Eifel. to Frasnian	17	?			⬤																		•		○	•		•			⬤				•		●	⬤
32. Turkey, Iran, Afghanistan	500	Eifel. to L. Fras.	15	33			●	•	•		⬤	○	●	•	○	●	•	•					⬤						•	●	●	●	●	●	•	•	•		○	○
33. Northern Africa, Morocco	800	Eifel. to Famennian	23	53	●	•	○	•	●	●	●	●	⬤	•	●	•				●	•	•		•				•	•	•	•	•	⬤	•		•	●		•	○
34. Russian Platform	600	Givet. to Famennian	15	40	•		●			•	○	●	⬤	○	•	○				●	●		●	⬤	•	●	●		●	•	○	○	○	•	○	•	•	●	○	●
35. Ural Mountains	1000	Eifel. to L. Fam.	16	62		•	•		●	•	○	○	○	•	•	•					•		⬤	●					•	⬤	•	•	○	•		•	•		•	●
36. Kuznetsk Basin, Middle Asia	800	Eifel. to Famennian	21	38			•			●	○	⬤	⬤	•	•	●				•	•		○						●	[illegible]	•	•	○	•	○	•	•		•	•
37. Altai Mts, Mongolia	1000	Eifel. to Famennian	25	40	●	•	•	•		○	⬤	●	○	●	●		•						⬤						•	⬤	•	•	○						●	•
38. Yakutsks, Sibiria	1400	Givet. to L. Fras.	8	175				•		○	○	○	●	•	•	•	•						•	•		○	○		⬤	●	•	•	⬤				•			•
39. Omolon-region, Sibiria	300	Givet. to Famennian	15	20							○	●	○	●	●	⬤									•				○	•		•	⬤				•			•
40. Southern China	900	Eifel. to Famennian	21	43	•	•	●		○	●	○	○	⬤	•	•	•	•						•	•					•	•	●	●	○	●	●	•	●		•	○
41. Vietnam	1300	Eifel. to L. Famen.	17	76						•	⬤	○	○		•					•			•	•					●	●	●	•	⬤	○	•					●
42. Eastern Australia	650	Givet. to U. Fras.	11	59						•	○	○	⬤		•					•			•	•					●	●	•	•	⬤	●	•					●
43. Canning Basin, W. Australia	800	Givet. to Famennian	23	35	•	•	●		●	●	○	○	○	●	•	○	•	•	•	•	•		○	•					•	•	●	○	○	•	○	●			•	●
44. New Zealand	200	Eifelian?	7	29							●		⬤	•	•	•				•									○	⬤				•					•	

Table 1. Quantitative and semiquantitative data concerning 44 characteristic areas of buildup growth (maximal thickness, time-span of sedimentation, sedimentation rate, and microfacies distribution. • rare microfacies or microfacies association; ● microfacies or microfacies associatiation building from 5 to 10% of the volume of the buildup complex; ○ from 10 to20% of the buildup complex; ⬤ more than 20% of the buildup complex.

Microfacies

a

association

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
A								◢	◢			◢						◢	◢	◢	◢		◢	
B					◢		◢	◢	◢			◢							◢					
C							◢	◢	◢	◢						◢								
D					◢		◢	◢	◢	◢									◢					
E					◢		◢		◢	◢		◢	◢						◢	◢		◢		◢
F					◢				◢	◢						◢		◢	◢	◢			◢	◢
G							◢	◢	◢							◢								
H						◢	◢				◢	◢												
I	◢	◢	◢	◢	◢																			
J					◢	◢	◢	◢	◢	◢	◢	◢							◢	◢				◢
K										◢	◢	◢	◢	◢	◢	◢	◢		◢					◢
L			◢	◢				◢											◢	◢	◢		◢	◢

stage

SMF

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1								◢	◢			◢						◢	◢	◢	◢		◢	
2					◢		◢	◢	◢			◢							◢					
3					◢		◢	◢	◢	◢						◢			◢					
4					◢		◢		◢	◢		◢	◢						◢	◢		◢		◢
5					◢				◢	◢						◢		◢	◢	◢			◢	◢
6	◢	◢	◢	◢	◢	◢	◢	◢	◢	◢	◢	◢				◢		◢	◢	◢			◢	
7					◢	◢	◢	◢	◢	◢	◢	◢							◢	◢				◢
8										◢	◢	◢	◢	◢	◢	◢	◢		◢					◢
9			◢	◢				◢											◢	◢	◢		◢	◢

b

Fig. 1. Qualitative correlation between standard microfacies types and microfacies associations (a), as well as between standard microfacies types and environmental stages (b).

1 Semilagoon
2 Coral and brachiopod banks
3 *Amphipora* banks
4 Stromatoporoid-coral patch reefs
5 Regressive lagoons
6 Shoals or barrier reefs
7 Reef-cap
8 Drowned reef surfaces
9 Non-reefal sedimentation

1985). The report evaluates about 350 papers which describe the facies data of 44 more or less precisely outlined areas of buildup growth (Table 1).

The areas considered are:
Western Canada: Leduc, Stettler and Redwater (ANDRICHUK 1958, KLOVAN 1964), Swan Hills (FISCHBUCH 1968, JANSA & FISCHBUCH 1974, VIAN & HARRIS 1983) Miette (NOBLE 197O, COOK 1972), Ancient Wall (SRIVASTAVA et al. 1972, MOUNTJOY & JULL 1978). Northwestern Territories of Canada (VOPNI & LERBEKMO 1972), Southeastern Alaska (SAVAGE 1977, SAVAGE et al. 1977) Pacific Northwest, Oregon, Washington and British Columbia (KLEWENO & JEFFORDS 1961, DANNER 1977), Nevada (MURPHY & DUNHAM 1977, POOL et al. 1977, SMITH & BISSEL 1984), Williston Basin, Dakota (LONGMAN 1981, WILSON 1975), Eastern USA, Appalachian region (WOLOSZ 1982, KOCH 1982, BAIRD & BRETT 1982), Cantabrian Mountains, Spain (BUGGISCH et al. 1980, PILGER 1974, HERBIG & BUGGISCH 1984), Montagne Noir (BIGEY 1983, SPALETTA et al. 1983), Southwestern England (SCRUTTON 1977a,b) Bretagne, France (LE MAITRE 1937, MORZADEC 1876, 1983), North Sea (BLESS et al. 1981), Dinantian Basin and Boulonnais (BRICE et al. 1976, MISTIAEN & PONCET 1983, LECOMPTE 197O, TSIEN 1975, 1979, BIRON et al. 1983, KASIG 198O), Eifel, Germany (STRUVE 1963, Faber 198O), Rhenish Schiefergebirge (KREBS 1968, 1971, 1974, JUX 1960, 1967, KREBS & WACHENDORF 1979, QUADE 1963, FLÜGEL & HÖTZL 1976), Harz (FRANKE 1973, LÜTKE 1976, PALME 1977, SCHNEIDER 1977), Moravia (HLADIL 1983a,b, SKOCEK 1979), Thuringia (GRÄBE et al. 1967, BLUMENSTENGL & GRÄBE 1968), Westsudeten region (CHLUPAC 1963, GALLE & CHLUPAC 1976, GUNIA & WIJCIECHOWSKA 1971), Pomerania, Poland (LOBANOWSKI 1968, STASINKA 1969), Krakow region (PAJCHLOWA & STASINSKA 1967, SLOSARZ & ZAKOWA 1975, NARKIEWICZ 1978), Holy Cross Mountains, Poland (ZAGORA 1983, RACKI & SZULCEWSKI 1981), Lublin depression (PAJCHLOWA & STASINKA 1967, STASINKA & NOWINSKI 1976, RADLICZ 1975), Northern Hungary (KULLMANOVA & BIELY 1979, MIHALY 1978, 1982), Carnic Alps and Karawanken, Southern Alps (SPALLETTA et al. 1983, 1974, TESSENSOHN, 1974), Serbia, Yougoslavia (FILIPOVIC et al. 1975, KOSTIC-PODGORSKA 1961), Bulgaria (BUDUROV & CHUNIEV 1964), Turkey, Iran, Afghanistan (ÜNSALANER 195O, FLÜGEL & FLÜGEL 1961, BLIECK et al. 1982), Northern Africa, Morocco, Algeria, Menorca, Betic Cordillera/Spain (HERBIG 1984, FLÜGEL & FLÜGEL 1979, WENDT et al. 1984), Russian Platform (SOKOLOV 1952, CHUVASHOV 1968, LIASHENKO et al. 1969, VORONOVA & RADIONOVA 1976), Ural Mountains and Novaya Zemlya (CHERNYSHEV 1937, KHODALEVICH et al. 1959, BREIVEL et al. 1972, KHALYMBADGA 1981), Kuznetsk Basin, Middle Asia (DUBATOLOV 1959, LAVRUSEVICH 1980), Rudnyi Altai, Mongolia (DUBATOLOV 1962, IGNATOV 1984, MARINOV et al. 1973, SHARKO-VA 1981, ADYAA 1971, VASSILEV et al. 1968), Yakutsk region (KHAIZNIKOVA 1974, 1975, ABRAMOV 1974), Omolon region (BARSKAYA 198O, SIDIACHENKO et al. 1970), Southern China (WANG et al. 1978, WENG & LUO 1983), Vietnam (BOURRET 1922, TONG-DZUY 1967, 198O, PHAN-CU 1981, PHAM-DINH 1981), Eastern Australia (JELL 1968, PEDDER et al. 197O), Western Australia, Canning Basin (COCKBAIN 1984, PLAYFORD et al. 1976, WILSON 1975), New Zealand (HILL 1956, BRADSHAW & HEGAN 1983). About 25% of the microfacies data used in this paper are based on communications of collegues.

The state of the art regarding the facies analysis of Devonian carbonate buildups varies depending on the density of bore holes and profiles and on some differences in the microfacies approach, especially in France and Russia. Nevertheless, the large amount of comparable data allows a statistical and empirical treatment of the major trend in the development of Devonian reefs.

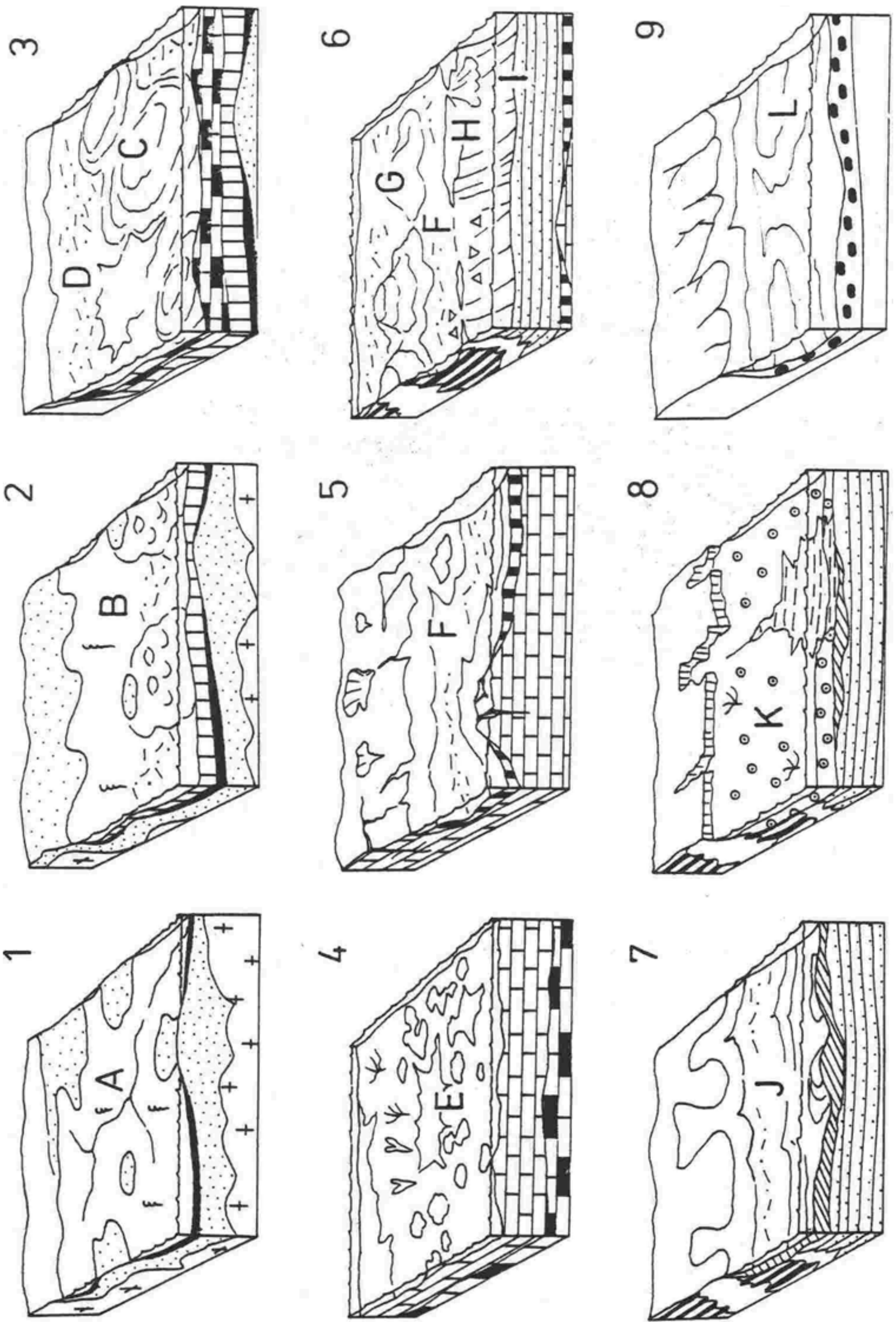


Fig. 2. Nine blockdiagramms showing the stages of growth of a buildup complex and the distribution of the microfacies associations. Association A growths directly on crystalline rocks and basal Devonian series.

2 VERTICAL SEQUENCE OF THE MICROFACIES

The vertical sequence of the microfacies of the Middle to Upper Devonian buildup complexes is predominatly controlled by the tectonic setting. The most common type (80%) is represented by rapidly subsiding platforms or quasiplatform blocks in miogeosynclinales (WILSON 1975): The carbonates were deposited in a hot dry climate of a circumequatorial belt (HECKEL & WITZKE 1979). It is assumed that the crustal layer was thinner than today; the earth's surface was relatively flat and the prevailing tectonic regime was characterized by a break-up of platforms and by persisting subsidence of large plates. The angle of the platform slopes was smaller than in recent examples. Such conditions may be reflected by the vast areas covered by back-reef sediments.

The fundamental characteristics of the vertical sequence were discussed by HOFFMAN & NARKIEWICZ (1977): The base of the sequence is characterized by coral banks with tabulate corals growing within a low energy zone. These banks are overlain by banks with tabular stromatoporoids. The true reef stage at the top of the profiles exhibits a differentiation into back-reef, reef margin and fore reef talus. HOFFMAN & NARKIEWICZ (1977) based their model mainly on examples from Canada and Germany. A similar sequence is documented by TSIEN (1984). This general sequence is also indicated by the microfacies sequence. The cyclic changes (KASIG 198O, MOUNTJOY 1980, LONGMAN 1981), however, and inhomogenities call for another strategy which traces the microfacies associations rather than just isolated microfacies types.

3 MICROFACIES ASSOCIATIONS OF MIDDLE TO UPPER DEVONIAN BUILDUP COMPLEXES

Twelve associations can be distinguished. They occur superposed from the bottom to the top, showing a higher degree of variability in later stages of buildup growth. The microfacies associations are assigned the letters A to L. Each association includes several standard microfacies types (Fig. 1).

Microfacies Association A (Plate 1/1): Dark coloured, sandy and dolomitic limestones predominantly micritic and biopelmicritic. Often algal laminites, cryptalgal nodules, and evaporites occur. Prevailing biota are ostracodes, chaetetids, favositids, cystimorph rugose corals, worms, bryozoans, gastropods, and thin-shelled brachiopods. Corals belonging to *Trachypora* may be characteristic in some places. Intercalations of black or scarlet shales may be present. This microfacies association corresponds mainly with the standard microfacies (SMF) 8, 9, 20, 21, and 23.

Association B (Plate 1/2-4): Dark coloured biointrarmicrititic coral beds with crinoid ossicles and thick-shelled brachiopods. In some places the coquina of *Bornhardtina* and/or *Stringocephalus* shells forms significant banks or lense-like bodies. Common fossils include heliolitids, favositids as well as some *Amphipora* stems, encrusting stromatoporoids and alveolitid corals. Intercalations of marls as well as irregularly shaped dolomite bodies are often reported. Possible correlations exist mainly with the SMF-types 5, 7, 8, and 9.

Association C (Plate 2/1): Variously coloured limestones predominantly micrite. Alternations of biosparitic and/or biointrasparitic beds form rhythmical sequences. Tabular stromatoporoids are frequent. *Girvanella* nodules may occur as well as dispersed tests of foraminifera (*Bisphaera* sp., *Cribrosphaeroides* sp., *Polyderma* sp.), and calcispheres. Many of the buried surfaces were biocemented early or covered. This microfacies association generally indicates some acceleration in the growth of the buildup. The most important SMF types relevant for this association are SMF 7 and 8.

Association D (Plate 2/2): Biomicritic *Amphipora* wackestone, usually included within cycles as described by KASIG (1980). The decimeter to meter-sized cycles consist of laminites, *Amphipora* layers, and boundstone layers. Alternations of homogeneous micrite and *Amphipora* layers, and together with biosparitic intercalations are also observed. A remarkable feature is the accumulation of bulbous stromatoporoids overgrowing corals in some horizons. Large patches of fossiliferous micrite with cryptalgal nodules contain spiralled gastropods or dendroid corals (*Disphyllum*, *Dendrostella* sp.). Most common are the SMF types 5, 7, 8, 9, and 19.

Association E (Plate 2/3, 4; 3/1): Light grey biomicrites and biosparites, often with boundstone textures. The highly diversified stromatoporoid and other fauna build thick banks and bioherm horizons. Endo- and epibiontic organisms are present, too. Thicker beds may contain small amounts of kerogene and pyrite. Bafflestone texture may be replaced by bindstone textures without a distinct lateral separation. Flat *Stachyodes* beds, *Clavidictyon-Idiostroma-Dendrostroma* patches, and mud mounds with *Actinostroma*, as well as patch-reefs with *Hermatostroma* have been observed. More common fossils are *Calipora* and *Crassialveolites* (Tabulata): Frequently occurring SMF-types are SMF 5 and 7, accompanied by many others (Fig. 1).

Association F (Plate 3/2; 4/1): Biomicritic *Amphipora* packstone, characteristic for the backreef environment. Rhythmical sequences consist of *Amphipora* packstones alternating with laminites. These laminites can be of algal as well as of non-algal origin. The accumulation of *Parathurammina* can be compared with those in recent lagoonal foraminiferal sands. Mottled dolomites are common. The abundance of tube-like thalli of the green alga *Issinella* is a conspicuous feature. Irregularly distributed rare patches with alveolitid corals and *Hexagonaria* as well as fenestellid bryozoans, trilobites and spiriferid brachiopods may occur. Silicified lagoonal intraclasts are common. The SMF types 5, 9, 10, 18, and 20 are frequent.

Association G (Pl. 4/2): Mostly micritic boundstones with encrusting algae, tabulate and rugose corals (*Thamnophyllum*). Corals are in life position. Conodonts

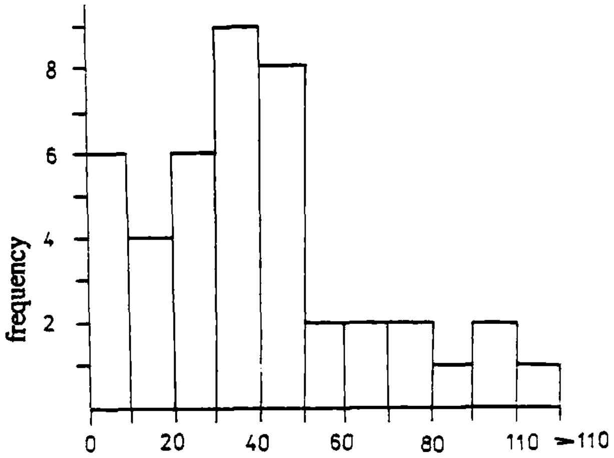


Fig. 3. Frequency of the sedimentation rates.

and crinoids are usually absent. The biofacies points to an intralagoonal bioherm environment. Vadose silt indicates occasional subaerial exposure. The SMF 7 is important for this microfacies association.

Association H (Plate 4/3): Biolithite with intrasparrudite and biointrasparite. Open-space structures within the rudstones correspond to stromatactis. Bio constructions of stromatoporoids and alveolitids, with some contributions of algae and crinoids. The rock may provide conodonts. Fore-reef detritus may be covered by tabular alveolitids. This facies indicates the existence of a reef margin and adjacent areas, situated within high energy environments. Important microfacies are included within SMF types 6 and 7.

Association I (Plate 5/1, 2): Fine-grained biointramicrite with layers of 'pelagic mudstones' or shales forming a typical fore-reef to off-reef microfacies association. Some intercalations of megabreccias consisting of large blocks and/or parabreccias consisting of plasticlasts as well as calcisiltites occur. The same holds true for graded limestone turbidites. Conodonts are common. The SMF types 1, 2, 3, and 4 are usually represented.

Association J (Plate 6/1, 2; 7/1, 2): Light grey, inhomogenous limestone often containing algae (Renalcis) and foraminifera (*Multiseptida, Geinitzina*, Tournayellidae). Biosparite and biomicrite with a clay admixture occur often in bioherms of fore-reef position; Nearshore banks are built by an *Amphipora*-Solenoporacean algal biomicrite. This associations is usually developed in the 'cap-position'. Massive phillipsastreoid corals, conodonts, and some cephalopods may be present. The spectrum of the microfacies types is very broad: predominantly SMF types 5, 7, 8, 9, 10, 19, and 24.

Association K (Plate 8/1, 2): Biosparite with some aggregate grains, intraclasts and oncoids. The foraminifera are highly diversified, algae are common.

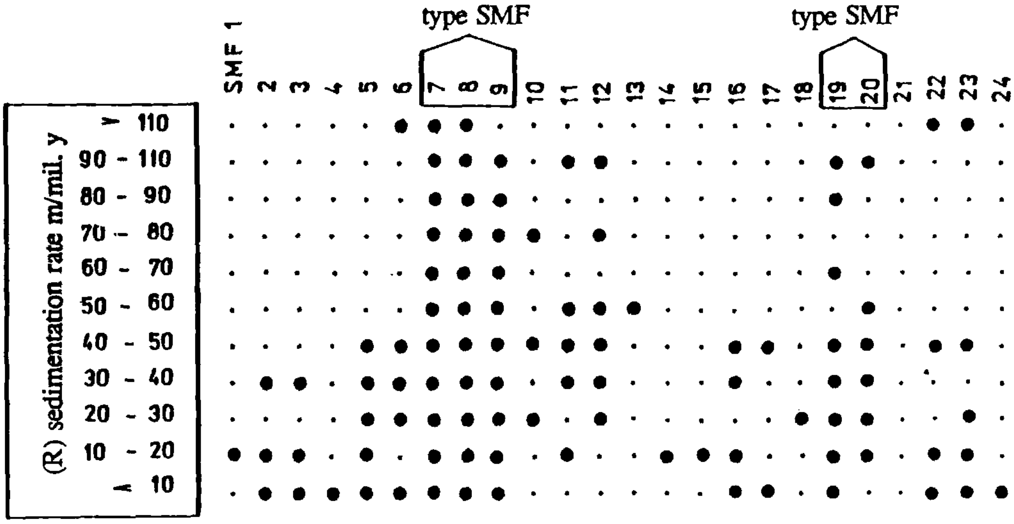
The rounded bioclasts consist of crinoids, mollusks, and ostracodes. Oolitic and/or pelletal horizons are characteristic. At some levels hard-ground paleosurfaces may be developed, bored by endolithic organisms and overlain by green shales. This association indicates a deposition on long persistent shoals formed on dead surfaces of buildups. It is observed within the upper parts of buildup- complexes, mainly at the top of whole complexes. It originates partly from the cannibalization of the buildup mass itself. This association can be compared with the SFM types 1O, 11, and 17.

Association L (Plate 9/1, 2): Fossiliferous micrites with clay admixtures and nodular structure. Teepee structures, stromatolites, lateritic material, refilled vugs, and breccias are observed in near-shore areas (DVORAK et al. 1976, WENDT et al. 1984). Accumulations of cephalopods and dacryoconariid tests are characteristic of a more off-shore position of the depositional environment. Ostracodes, trilobites, epiplanctonic brachiopods, porifera and radiolaria are scattered within the dark, condensed and non-bioturbated sediment. Fissures near the shoreline are filled similar to neptunian dykes. The most important SMF types are SMF 3, 19, and 24.

The classification into 12 microfacies associations is only a rough scheme based on average clusters of thin microfacies layers. Within each cluster many (more than ten) microfacies types can be distinguished; many of them have been already described.

Carbonate buildups on volcanic elevations in basinal position and/or on island arcs (less than 20% of the total record investigated) are characterized by the poor development of the associations A, B, H, I, J, K, and L.

In the model presented here the bioherms of Upper Famennian age are not included because they are not part of the main buildup complexes.



● significant SMF- more than 10% volume of the complex

Fig. 4. Relation between the sedimentation rate and the distribution of the standard microfacies

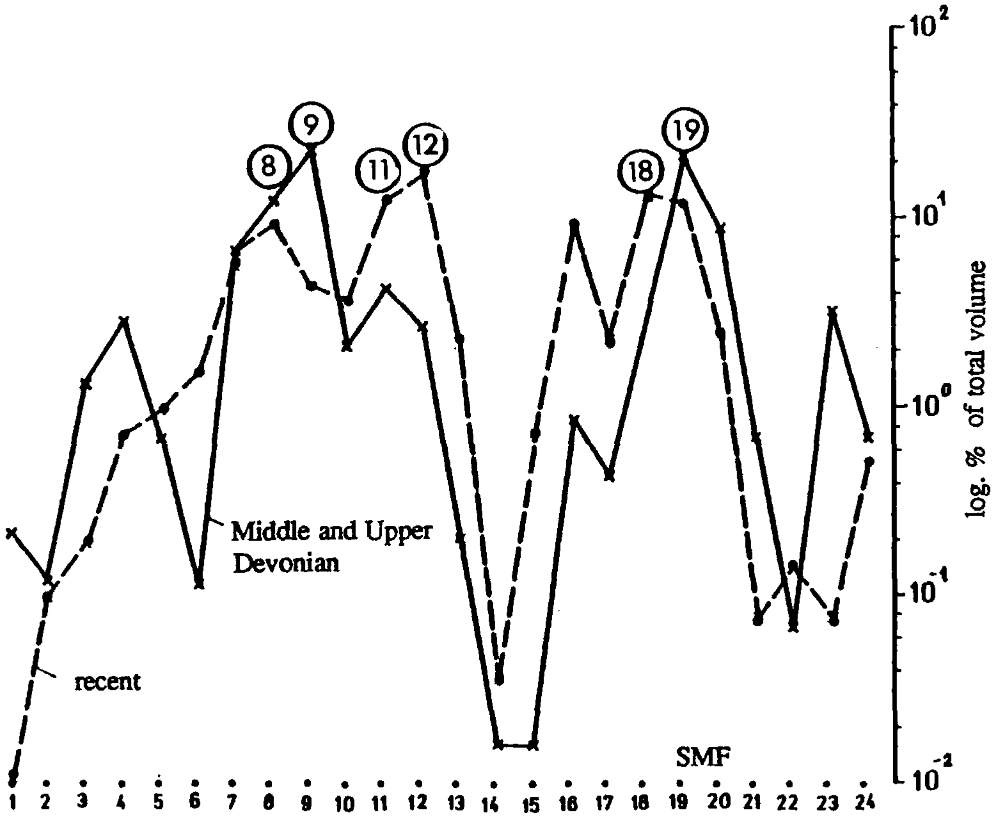


Fig. 5. Comparison of the SMF-type distribution in Middle to Upper Devonian and in recent buildups.

4 ENVIRONMENTAL GROWTH STAGES OF THE MIDDLE TO UPPER DEVONIAN BUILDUP COMPLEXES

According to HOFFMAN & NARKIEWICZ (1977) and KREBS (1971) we can roughly distinguish 4 stages: the semi-lagoonal stage, coral bank, true reef, and reef cap. TSIEN (1984) proposes a division into three stages corresponding to the early colonization stage, the biohermal and biostromal stage and the barrier reef and atoll stage. These approaches can be best defined by the distribution of the 12 microfacies associations described above. The evolution of the buildup complexes in the Middle and Upper Devonian is illustrated by a sequence of 9 stages (Fig. 2):

1. A semilagoonal stage with pioneer bentic communities
2. A stage of coral and brachiopod banks
3. A stage with *Amphipora* banks and flat mudmounds with stromatoporoids
4. A stage with stromatoporoid-coral banks occurring in scattered patch-reefs
5. A lagoonal stage generally regressive
6. A stage with shoals or barrier reefs (including a fore-reef development) as well as reef margins with a back-reef facies
7. A reef-cap stage indicating the end of the reef growth
8. A stage of drowned reef surfaces with carbonate sands and gravels
9. A stage characterized by the beginning of a non-reefal sedimentation (mainly nodular limestones)

This model, constructed from the viewpoint of environmental stages, includes some event-type levels or intervals. The same holds true for the model constructed form the viewpoint of megacycles (Chapter 6). The most prominent 'event' seems to be connected with the important regression of the boundary between the lower *Polygnathus asymmetricus* and the lowermost *P. asymmetricus* Zone of the Frasnian.

5 RATE OF CARBONATE SEDIMENTATION, CORRELATION WITH STANDARD MICROFACIES

The maximum buildup formation took place within the upper photic zone, at a depth of a few meters; the rate of sedimentation and the rate of subsidence, therefore, should be in a certain equilibrium (ADEY 1978). The intercalation of growth, destruction and non-sedimentation creates the difference between the growth rate of the bank and that of the buildup complex. This difference is approximately a rate of 1000:1. The growth rates of the buildup complexes are compiled in Table 1; their frequency is shown in Fig. 3. Age data are taken from HARLAND et al. (1982) and PALMER (1983).

The lowest sedimentation rates are present in the Wetsudetic region (0.8 m/my), in Thuringia (1.1m/my), the Eastern USA (4 m/my), the Carnic Alps (7 m/my), in Serbia (9 m/my); see Table 1.

The highest values are found in the Yacutsk region in the SSSR (175 m/my), the Rhenish Schiefergebirge (1oo m/my), and in Southeastern Alaska (100 m/my).

The rates of sedimentation vary strong even within

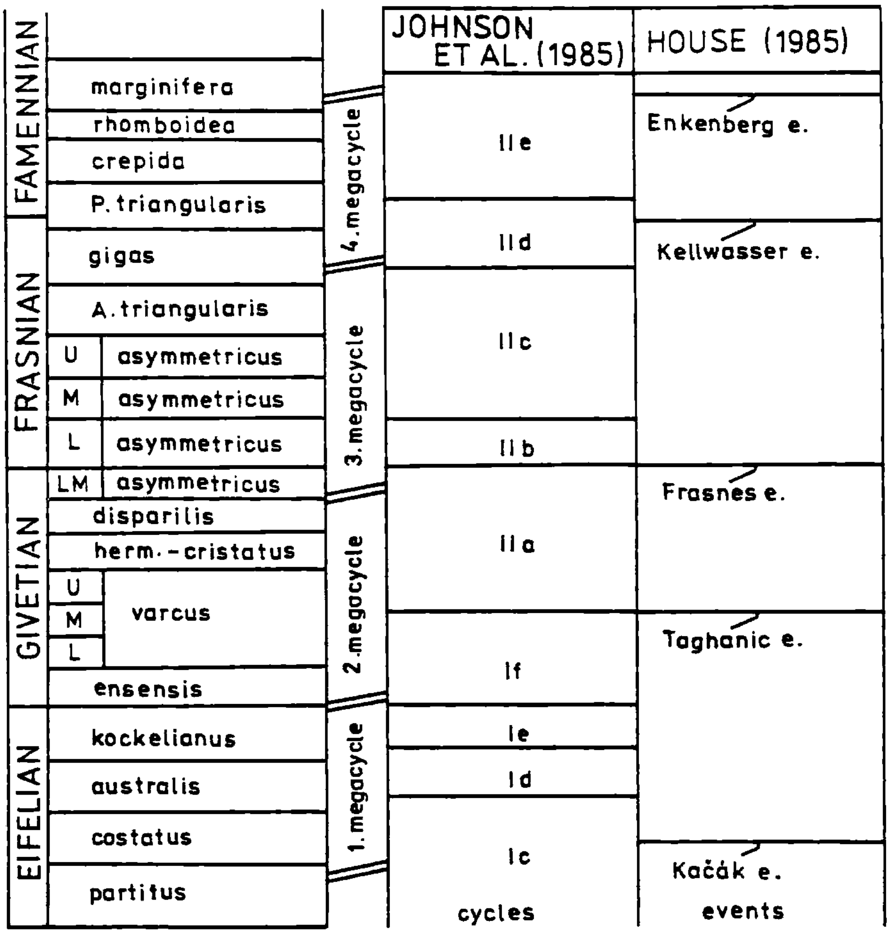


Fig. 6. Simplified correlation of event concepts, proposed by the author (megacycles, predominantly caused by varying tectonic situations) JOHNSON et al. (transgressive-regressive cycles, generated by eustatic sea level fluctuations), and HOUSE regressive events, derived from the evolution of ammonoid faunas). The boundaries of the megacycles vary slightly in time and space.

one region. In Moravia the minimum rate is known from Nizky Jesenik Mountains (10 m/my) and the maximum rate is described from the eastern slope of the middle part of the Bohemian Massif (133 m/my).

The correlation of the SMF distribution to the rate of sedimentation is illustrated in Fig. 4. In this diagram we can define SMF types, i.e., SMF 8, 9, and 19. These three SMF are typical of about 65% of the total sedimentation volume. The decrease in sedimentation is caused either by a deceleration of the subsiding base in the back-reef area or by an enormous subsidence of the fore-reef, especially at the end of buildup growth. A frequently observed emerging of back-reef areas connected with a drowning of the for-reef are seems to be caused by an inclination of blocks.

Characteristic of all the buildup complexes studied in this paper seems to be the intense pigmentation of rocks due to their pyrite and kerogene content, as well as the great predominance of a micritic matrix caused by an enormous precipitation of calcium carbonate by green algae and bacteria in a warm/hot shallow environment.

Comparison of estimated curves for the distribution of the SMF during the Middle to Upper Devonian with recent reefs shows some differences (Fig. 5). The SMF types 8, 9, and 19 are most frequent in Devonian reefs, the SMF types 11, 12, and 18 predominant in recent reefs. The data for recent reefs are based on the papers by BATHURST (1971), COURDAY (1977), IMBRIE & PURDY (1962), LUCIA (1968), MACINTYRE & GLYNN (1976), MESOLELLA et al. (1970), REVELLE & EMBRY (1954), VIDETICH & TREMBA (1978), WEYDERT (1976), and WILSON (1975).

6 CYCLIC PATTERNS OF DIFFERENT ORDERS

Cycles of varying magnitude and order are developed in the Middle to Upper Devonian buildup complexes. Cycles of the first order and a magnitude of about 10^{-1} to 10^{0}m are described by KASIG (1980), the second order cycles with a magnitude of 10^{1}m have been described by many authors (KOVERDYNSKY 1961, FISCHBUCH 1968, JANSA & FISCHBUCH 1974), megacycles of the third order with a magnitude of about 10^{2}m/my are described by HLADIL (1983a, b). The number of cycles or their order can increase.

Mainly the cycles of higher orders (the megacycles) seem to be controlled by some factors of planetary events, although smaller trends in their development are often camouflaged by local tectonics and climatic patterns. JOHNSON et al. (1985) compiled a detailed model based on eustatic events: HOUSE (1985) presents several causes of events: impacts, volcanic activity etc. In

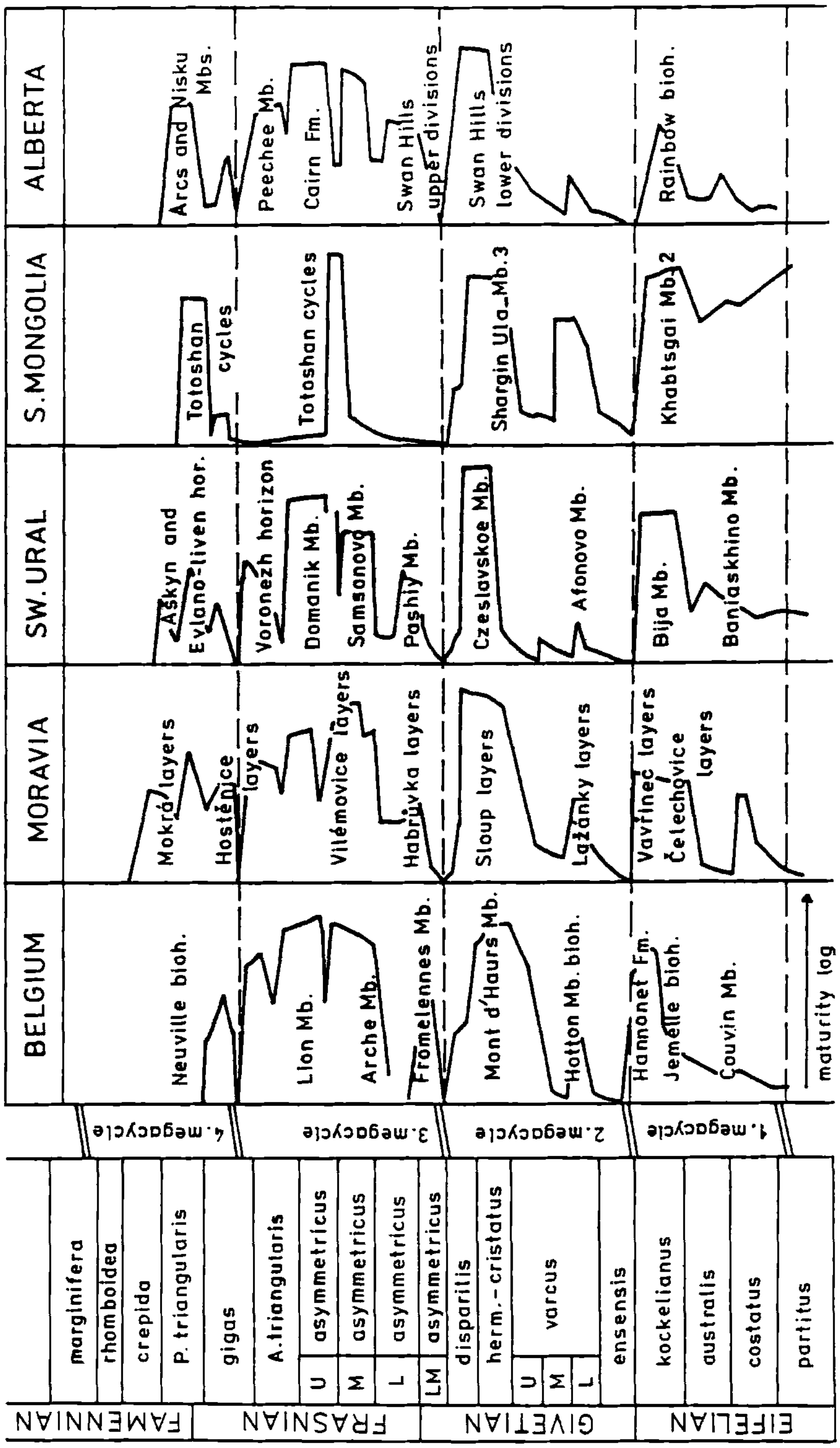


Fig. 7. Correlation of major Middle and Upper Devonian reef developments. The 'maturity' indicates the relative stage of growth of banks and/or reefs (poor maturity at the left).

our opinion the main cause for an event is the tectonics: this may either be changes in the type of tectonics connected with the intensity of the volcanic activity, or variations in the gravitational constant (MILANOVSKI 1982). To some extent other extraterrestrial influences may be important, too (variations of solar activity causing eustatic or thermal influences or meteoric impacts and/or bombardment).

The typical vertical sequence of the microfacies in cycles is analog to the sequences described by KASIG (1980): dark coloured micritic limestones (laminites) are overlain by *Amphipora* banks which grade into light coloured boundstones with a higher diversity in the biota Usually some sediments typical of a regression blanket are added. Most important is the interference of the vertical trends of the cycles. The interference of these trends creates specific features of the rock in each level of the buildup complex.

Four important megacycles can be distinguished in the Middle to Upper Devonian buildup complexes. They are usually separated by regression levels characterized by clastic intercalations, gaps, paleokarst, muddy admixtures

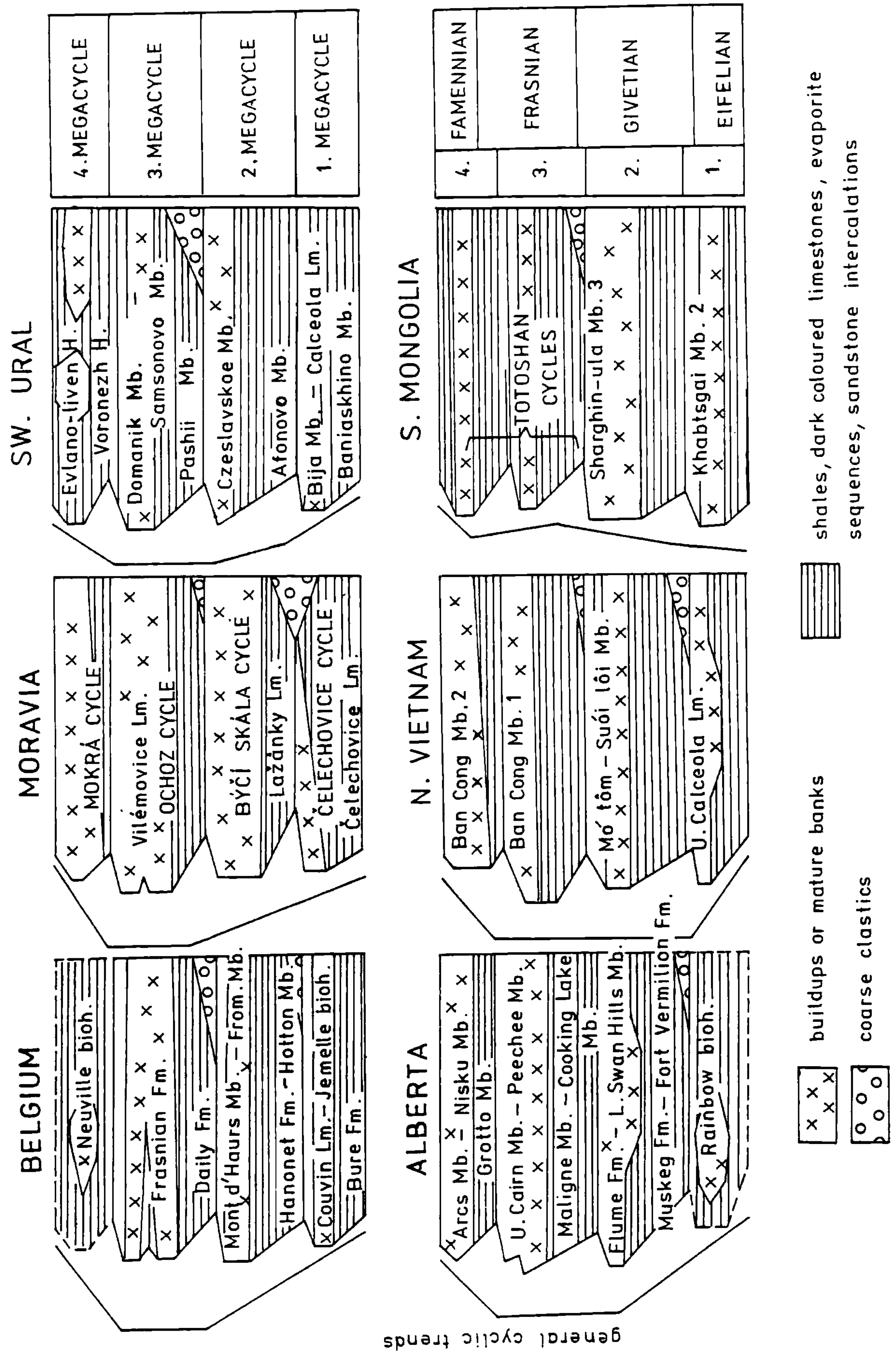


Fig. 8. Comparison of Devonian reef megacycles in Europe, Asia and Northern America.

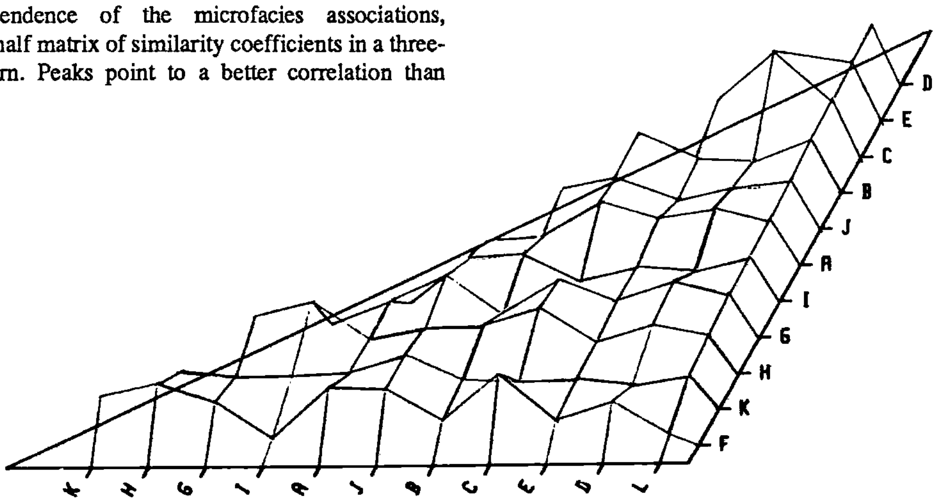


Fig. 9. Interdependence of the microfacies associations, expressed by the half matrix of similarity coefficients in a three-dimensional pattern. Peaks point to a better correlation than depressions.

or intraclast horizons.

The **first megacycle** is limited to the upper Eifelian. The culmination of the megacycles coincides with the conodont zone *Tortodus kockelianus*. This megacycle includes in any case the cycles Id to Ie of JOHNSON et al. (1985) (Fig. 6). The most important feature is the relatively large number of coral banks with frequent bryozoans and crinoids. The occurrence of the microfacies associations A, B, and C is characteristic.

The **second megacycle** covers sediments of the Givetian, reaching its maximum during the middle and upper part of the *Polygnathus varcus* Zone, which can be approximately correlated with the cycles If and especially IIa of JOHNSON's concept (Figs. 6 and 7). The second megacycle is characterized by the widespread distribution of "*Amphipora* wackestones", stromatoporoid -coral banks, dome-like reefs and mud-mounds. A, C, D, and E dominate among the microfacies associations.

The **third megacycle** started in the uppermost Givetian and culminated in the Lower Frasnian, while the top of the megacycle is placed in the *Palmatolepis gigas* Zone. The composition of this megacycle is complicated, but as a rule it consists of three stages (compare Figs. 6 and 7). Typical is the development of zonal shoals or barrier reefs. Most frequent are the microfacies associations F, G, H, and I.

The **fourth megacycle** is of Upper Frasnian and Lower Famennian age, reaching its maximum near or in the *Palmatolepis gigas* Zone, with its end placed near the Enkenberg event (cf. HOUSE 1985). Remarkable sediment types are *Amphipora*-algal limestones. The most characteristic microfacies associations are J, K, and L. The continuation of the buildup growth into the Lower Famennian is known from the eastern part of the Russian Platform (CHUVASHOV 1968, FRIAKOVA et al. 1985) as well as from Moravia (FRIAKOVA et al. 1985). The second occurrence is known from the Toto Shan Mountains in the Gobi desert of Southern Mongolia (MARINOV et al. 1973). A similar situation can be assumed for Canada and Poland. A comparison with the various events described in the Western United States by SANDBERG et al. (1983) shows the importance of the Upper Givetian transgression.

7 FINAL REMARKS

This paper does not intend to impose a time-table on the objects studied, because of the extremely large interference from various factors. However, we can observe some general trends which can be distinguished from many often controversial details with the help of numerical evaluation. This paper is very generalized and discusses only a few select results.

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Plate 1 Development of Middle and Upper Devonian Buildups
Microfacies Associations A and B

Fig 1. Laminites with sand admixture, intraclasts and light lamina of coarse sparit probably replacing evaporites. Lower Givetian, *Trachypora dubatolovi, Scoliopora dubrovensis* coral zone (HLADIL 1983b), Tisnov V 23 borehole, 86,3m. Microfacies association A. Natural size.

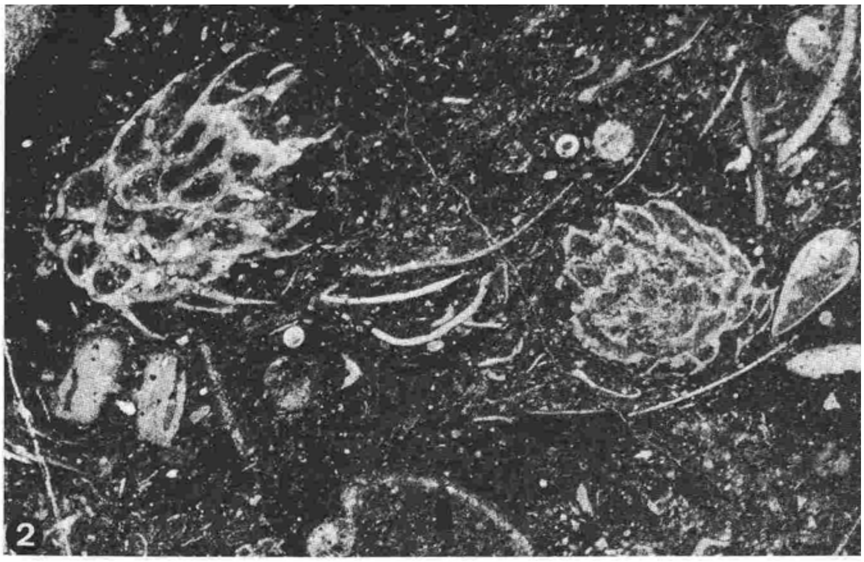
Fig. 2. Biomicrite packed with unsorted bioclasts including the stems of *Celechopora* sp. Uppermost Eifelian: Probably *Tortodus kockelianus* conodont zone. Celechovice Quarries, Moravia. Microfacies association B. x 6.7

Fig. 3. Tufaceous biomicrudite with many porifera spicules and with corals. Eifelian: upper part of the *Alveolites levis grandis* coral zone. Dzurkhein Nuur, Mantakh Somon, Mongolia. Microfacies association B. x 6

Fig. 4. *Bornhardtina* biomicritic layers with clay admixture and slight dolomitization. Lower Givetian - *Trachypora dubatolovi, Scoliopora dubrovensis* coral zone (HLADIL 1983b). Amaterka Caves, Moravian Karst, Moravia. Microfacies association B. x 0.06

TAFEL 1


1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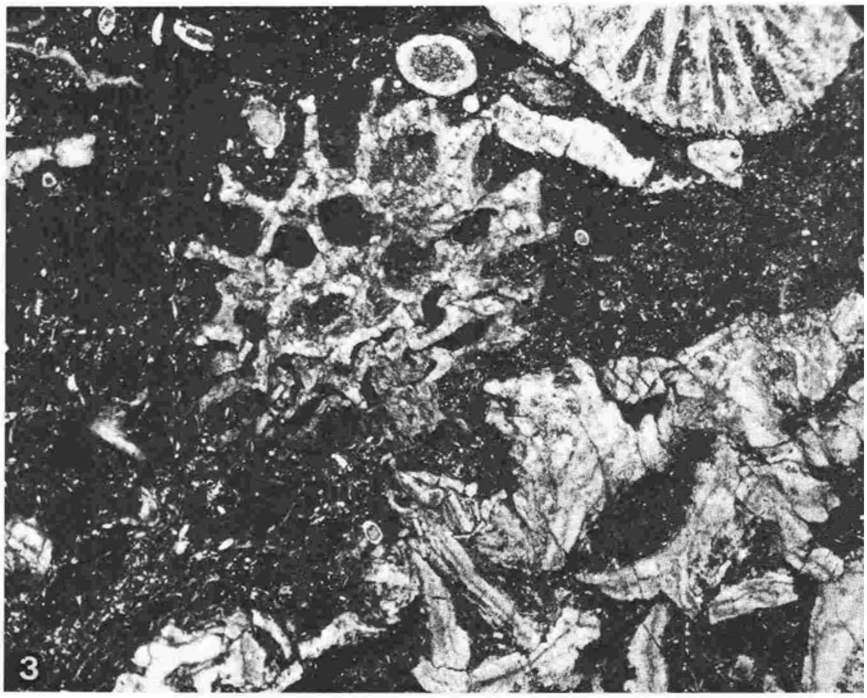
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Plate 2

Development of Middle and Upper Devonian Buildups
Microfacies Associations C, D and E

Fig. 1. Biomicrite and biosparite with large stromatoporoid layers of *Hermatostroma* sp. and *Parallelopora* sp., Middle Givetian: lower part of *Caliapora battersbyi-* coral zone (HLADIL 1983b). Amaterka Caves, Moravia. Microfacies association C.

Fig. 2. Laminite with scarce plasticlasts, *Amphipora-* layers and layers with a diverse stromatoporoid fauna i.e., KASIG's thin cycle. Lower Givetian - upper part of the *Trachypora dubatolovi, Scoliopora dubrovensis* coral zone (HLADIL 1983b). Sloup 1 borehole, 367.9m, Moravian Karst, Moravia. Microfacies association D. x 0.3

Fig. 3. *Stachyodes* biosparrudite, weathered surface of rock. Upper Givetian - upper part of the *Caliapora battersbyi* - coral zone. Doline T 4, Suchy zleb Valley, Moravia. Microfacies association E. x 0.3

Fig. 4. Biolithite to biomicrudite with amphipors, *Caliapora* ex gr. *omolensis*, and *Actinostroma* sp.. Upper Givetian - - upper part of *Caliapora battersbyi* coral zone (HLADIL 1983b). Kozlovice SV 1 borehole, 2122.7m, northeast of Ostrava, Moravia. Microfacies association E. x 3.7


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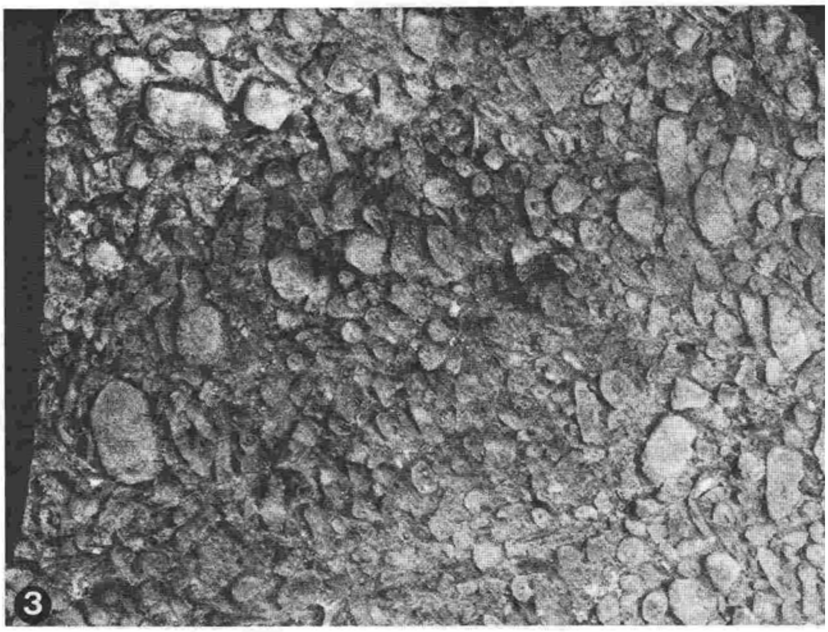
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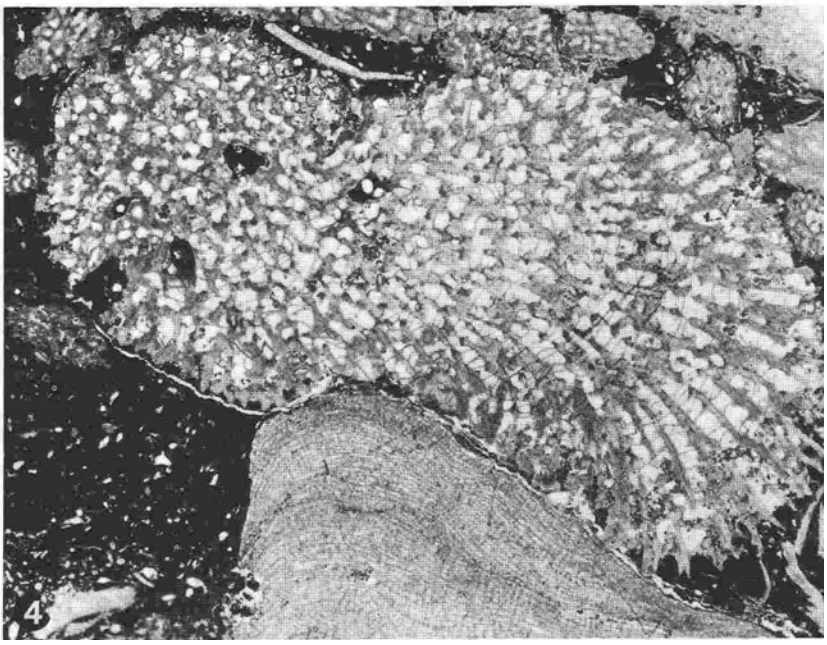
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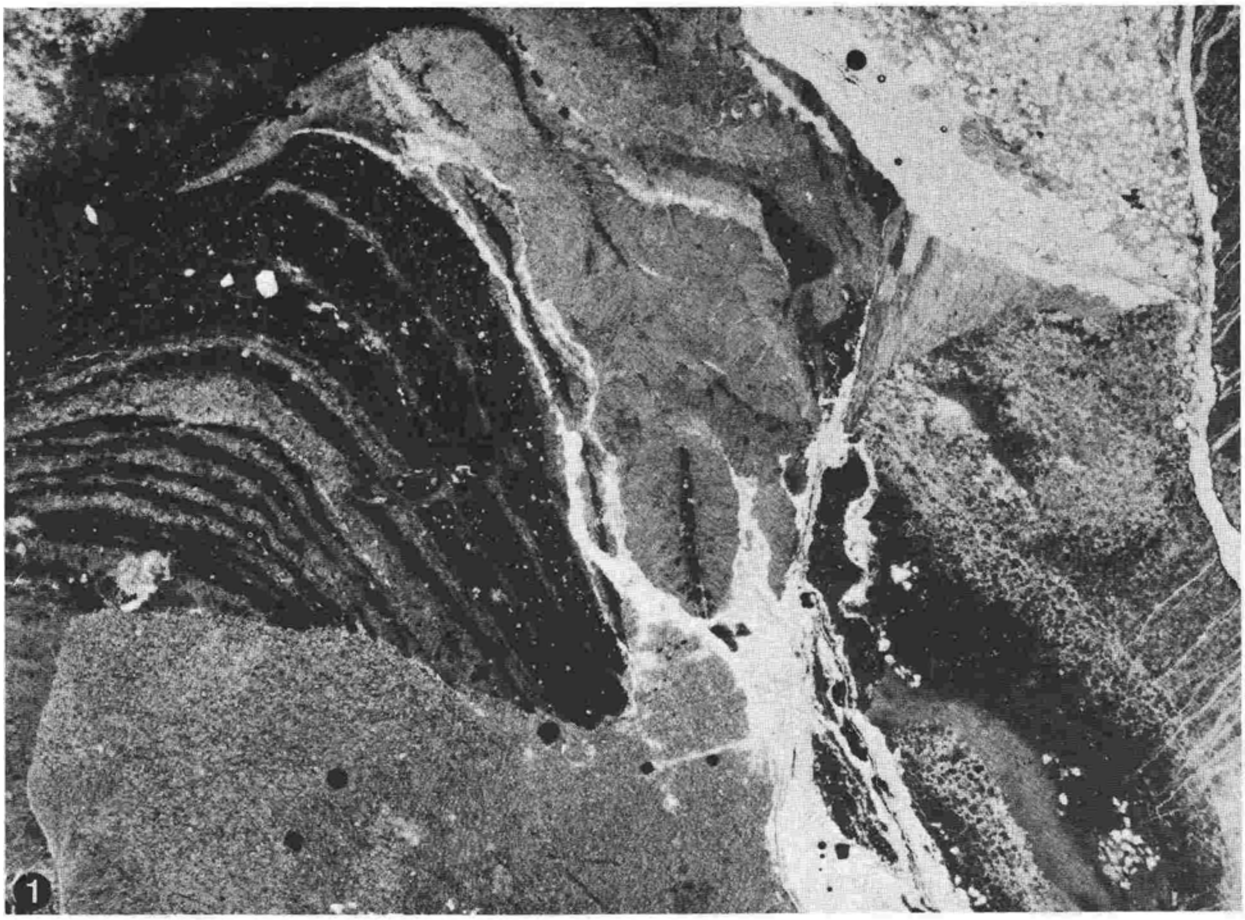
Plate 3 Development of Middle and Upper Devonian Buildups
Microfacies Associations E and F

Fig. 1. Rudstone of the standard microfacies no. 24. Upper Givetian - *Caliapora battersbyi* coral zone (in part an equivalent to the *Schmidtognathus hermani, Polygnathus cristatus* conodont zone). Krasna KS 1 borehole, 1402.4m, southeast of Ostrava, Moravia. Microfacies association E. x 8.2

Fig. 2. Accumulation of *Amphipora* stems in poorly washed biosparite with foraminifers, ostracods, pellets and peloids. Lower Frasnian. Koberice 1 - borehole, 970.0m, southeast of Brno, Moravia. Microfacies association F. x 8.2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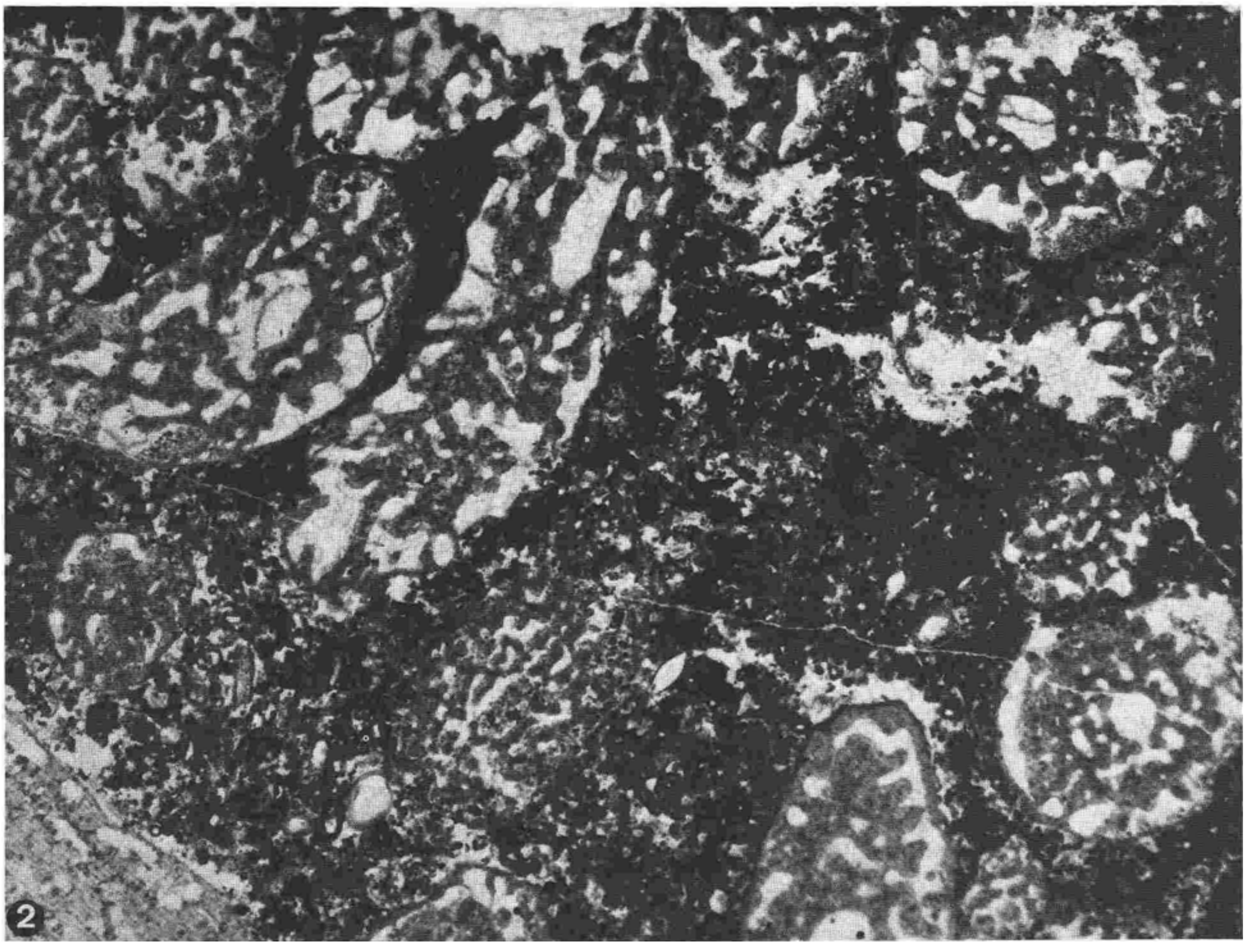
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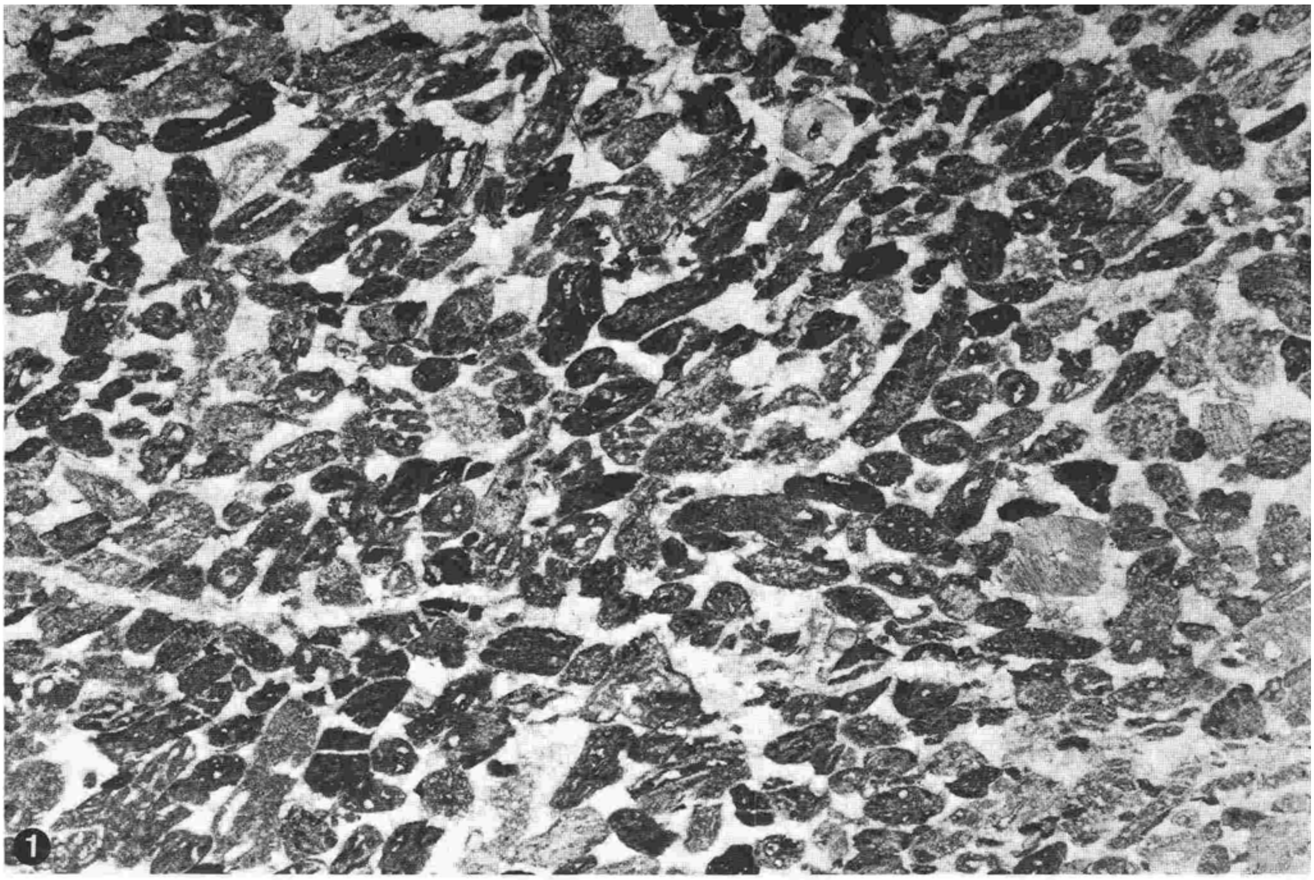
Plate 4 Development of Middle and Upper Devonian Buildups
Microfacies Associations F, G, and H

Fig. 1. Biosparite with *Stachyodes* debris and scarce crinoid ossicles. Lower Frasnian - Lower *Polygnathus asymmet ricus* conodont zone?. Lazanky Great Doline, Moravian Karst, Moravia. Microfacies association F. x 8.5

Fig. 2. *Thamnopora boloniensis* and *Stachyodes costatus* form a bafflestone structure. Interspaces are filled with micritic matrix. Upper Frasnian - *Ancyrognathus triangularis* conodont zone. Hlady V 103 - borehole, 80.0m, north of Brno, Moravia. Microfacies association G. x 1.0

Fig. 3. Phillipsastraeid coral fragments in biosparite with some small algal lumps. Lower Frasnian - *Alveolites delhayei* coral zone, equivalent to *Polygnethus asymmetricus* conodont zone?. Vilemovice Canyon, Moravian Karst, Moravia. Microfacies association H. x 8.2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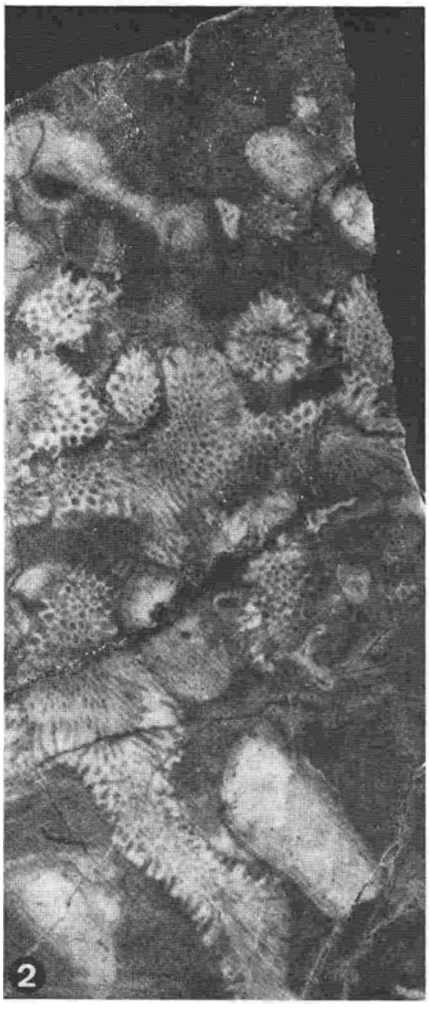
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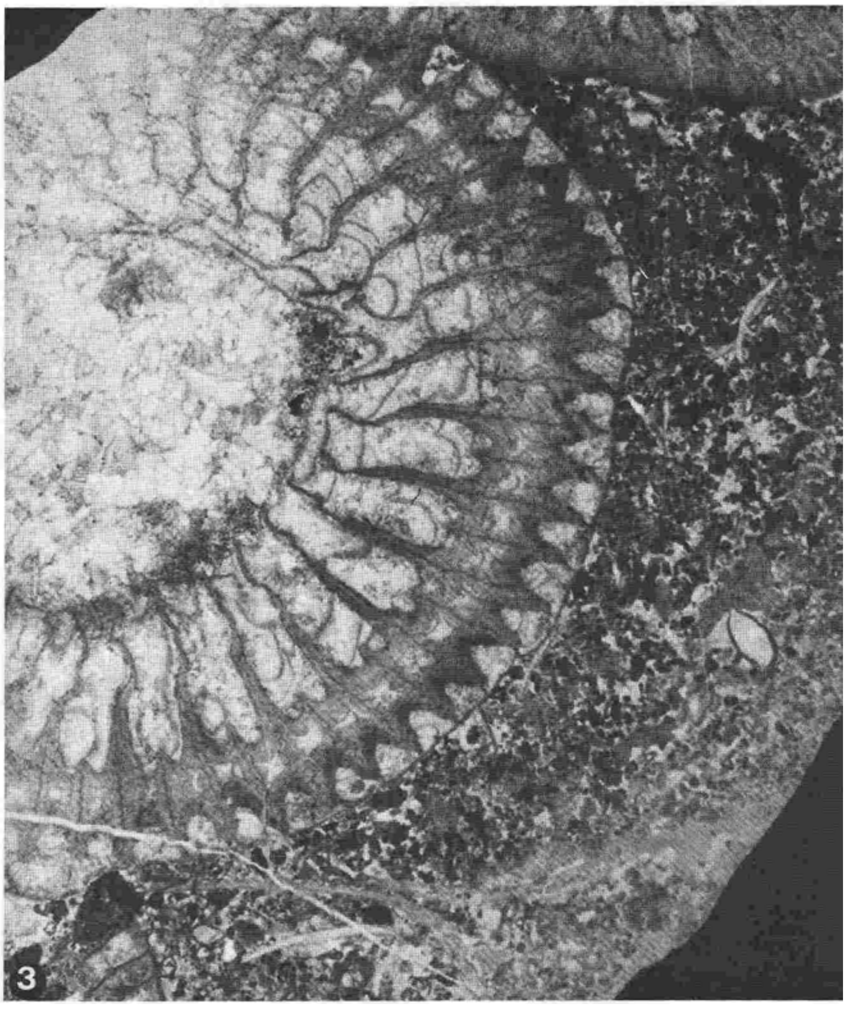
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Plate 5 Development of Middle and Upper Devonian Buildups
Microfacies Association I

Fig. 1. Accumulation of dacryoconariid test with fragments of rugose corals and with intraclasts of limestone with crinoid ossicle and scarce dacryoconariid tests. Lower Frasnian: Middle *Polygnathus asymmetricus* conodont zone. Horni Benesov HB 56 P borehole, 115.5m. Microfacies association I. x 7.8

Fig. 2. Tuffaceous limestone with large pteropods, crinoid ossicles, fragments of bryozoans, porifera spicules and conodonts. Upper Famennian: *Palmatolepis marginiferato Palmatolepis postera perlobata* conodont zones. Horni Benesov HB 934 borehole, 84.2m, Moravia. Microfacies association I. x 6

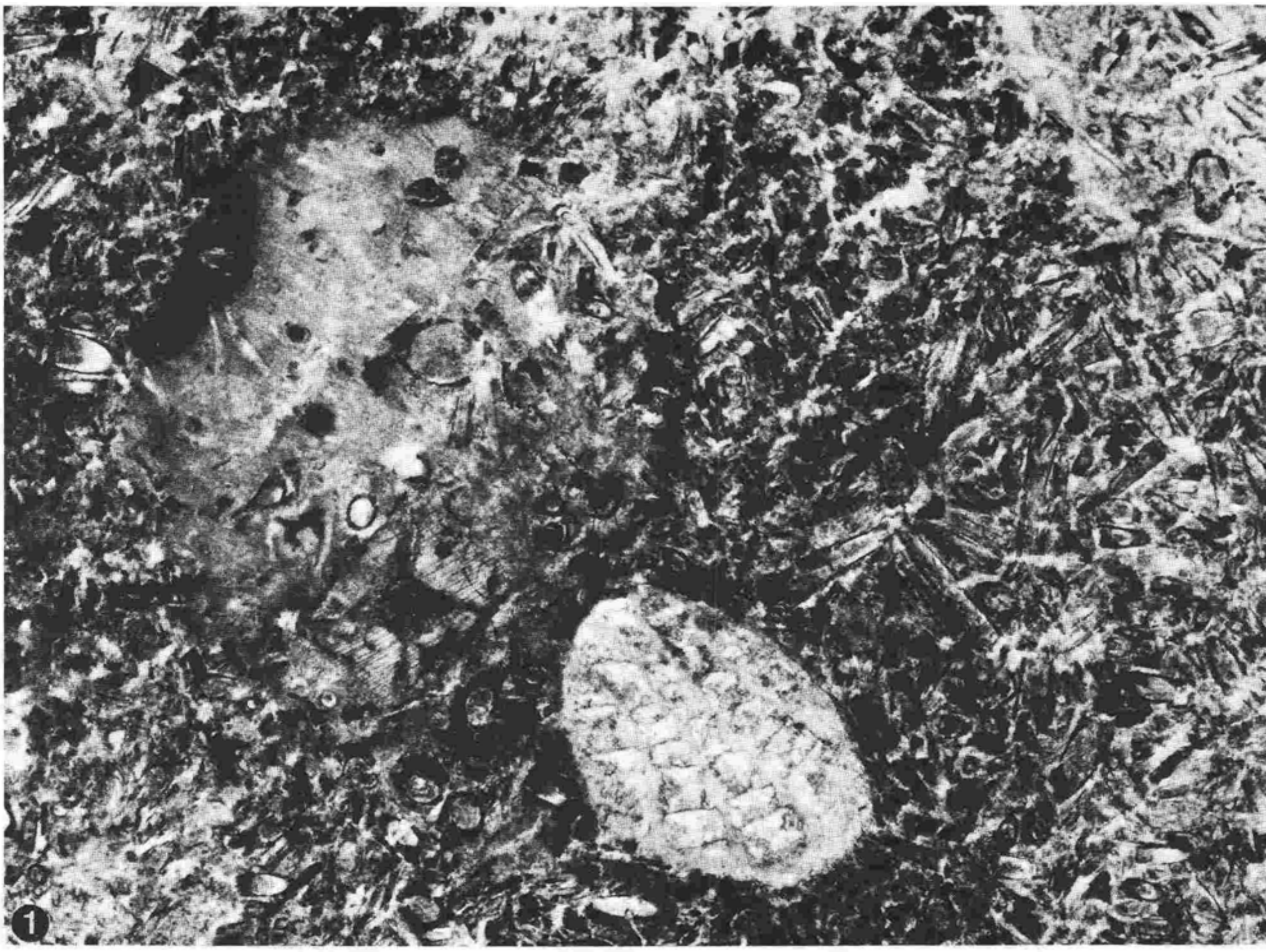

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Plate 6 Development of Middle and Upper Devonian Buildups
Microfacies Association J

Fig. 1. Biosparrudite with rugose corals, *Stachyodes* and algal crusts bounded by *Alveolites delhayei, Tyrganolites frasnianus* and *Clathrocoilona* sp.. Upper Frasnian. Upper *A. triangularis* conodont zone. Krtiny HV 105 borehole, 178.2m, Moravian Karst, Moravia. Microfacies association J. x 3.3

Fig. 2. Accumulation of *Scoliopora* branches in biomicritic limestone with debris of algae and vagile benthos. Upper Frasnian. *Polygnathus gigas* conodont zone. Kalkgraben in the Swiebodzice Depression betwen Kaczawskie Mts. and Sowie Mts., Poland. Microfacies association J. x 7.1

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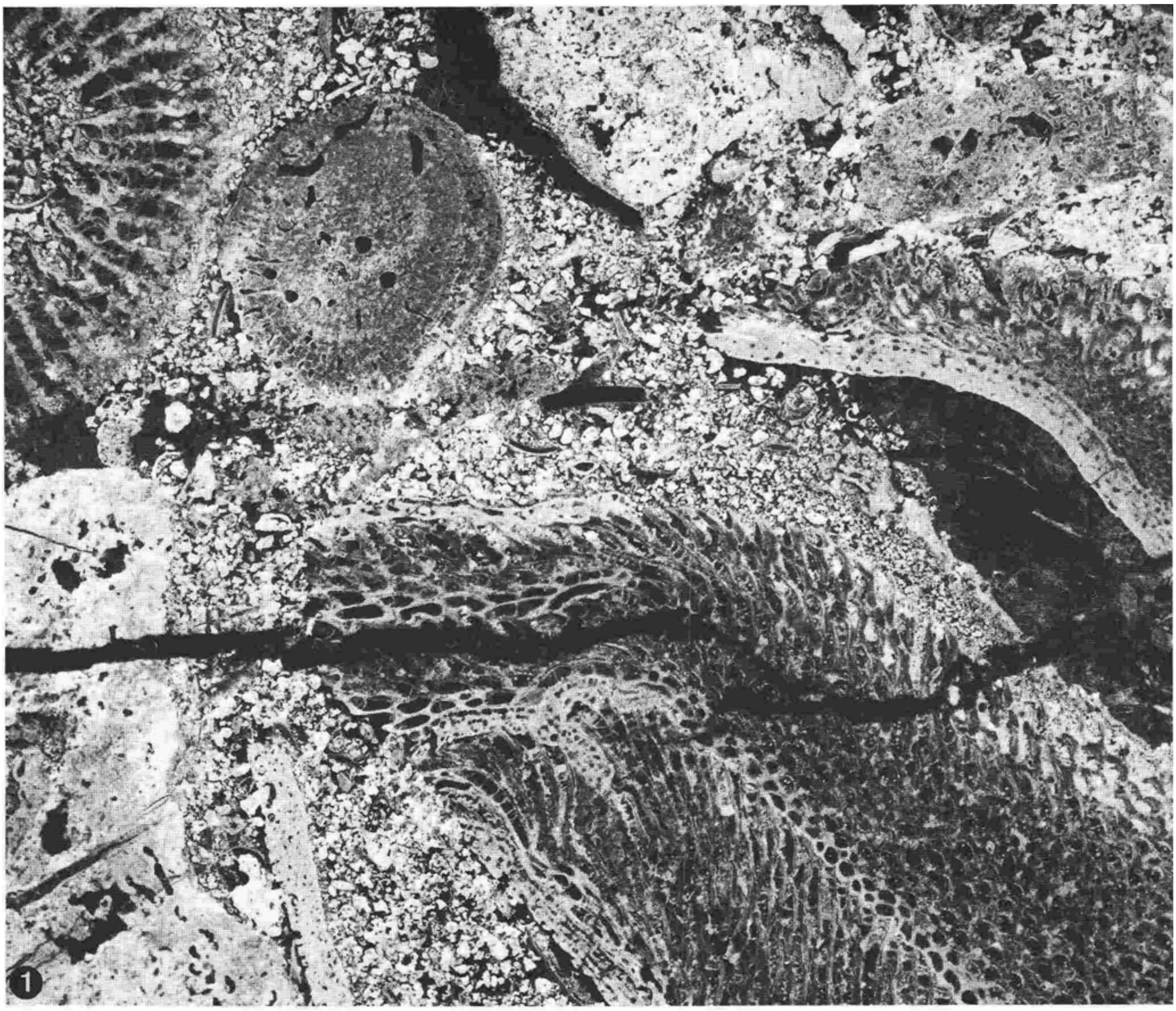

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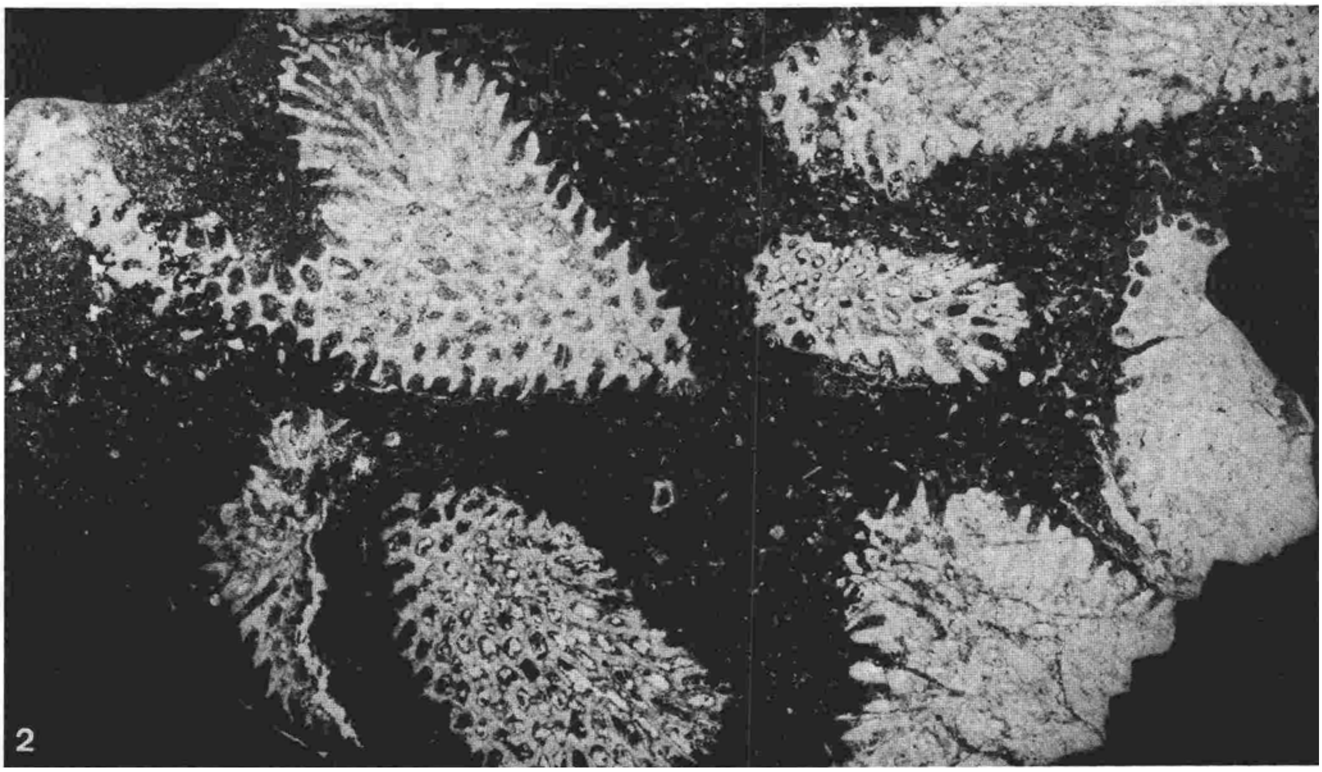

Plate 7 Development of Middle and Upper Devonian Buildups
Microfacies Association J

Fig. 1. Biolithite formed by multiple overgrowth of alveolitid corals. Upper Frasnian: Limits of *Palmatolepis gigas* and *Palmatolepis triangularis* conodont zones. Vokoun's Cave near Krtiny, Moravia. Microfacies association J. x 7.1

Fig. 2. Bafflestone texture with Solenoporaceae indet. and *Amphipora* stems. Lower Famennian. Border between *Palmatolepis triangularis* and *Palmatolepis crepida* conodont zones. Mokra Quarries, Moravia. Microfacies association association J. x 8.2

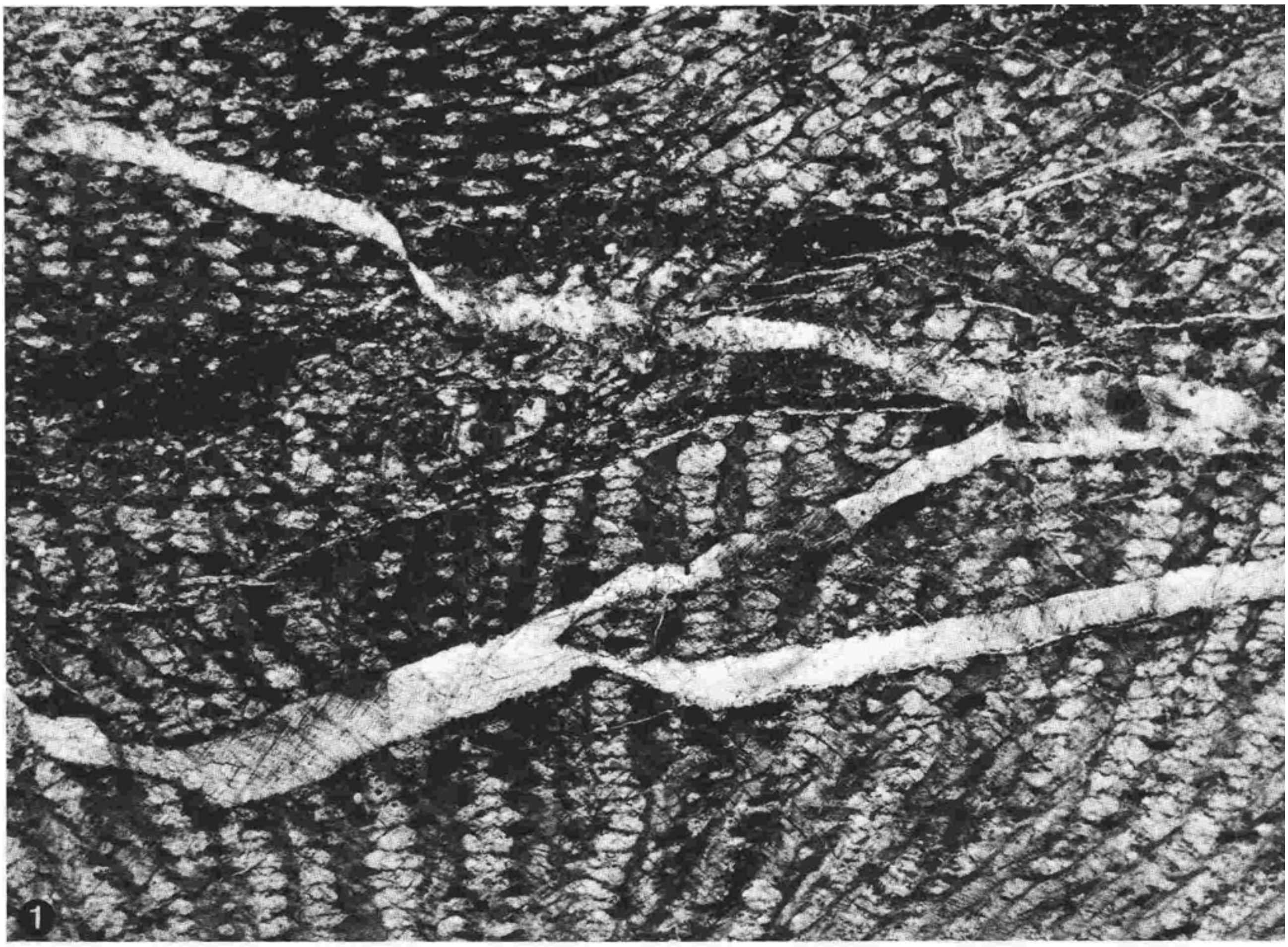
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Plate 8 Development of Middle and Upper Devonian Buildups
Microfacies Association K

Fig. 1. Biosparrudite with algal oncoids and lumps. Upper Frasnian: *Palmatolepis gigas* conodont zone. Kalkgraben in the Swiebodzice Depression between Kaczawskie Mts. and Sowie Mts., Poland. Microfacies association K. x 5

Fig. 2. Biosparite layers covered by poorly washed layer. Bio- and lithoclasts are micritized. Lower Famennian- local foraminifer zone "no. 5" , comparable to *Palmatolepis crepida* zone. Uhrice 14, core no. 9, southeast of Brno, Moravia. Microfacies association K. x 5.2

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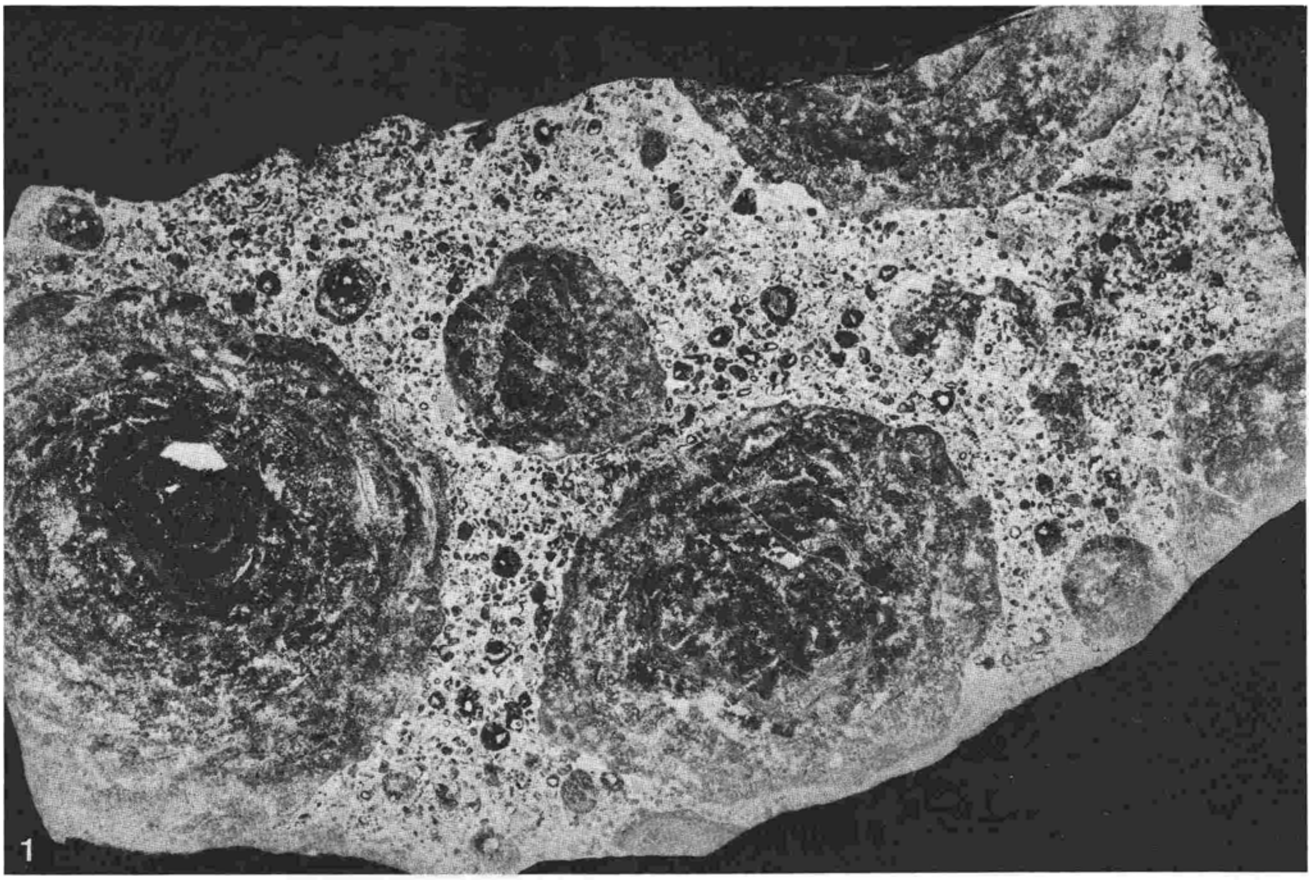

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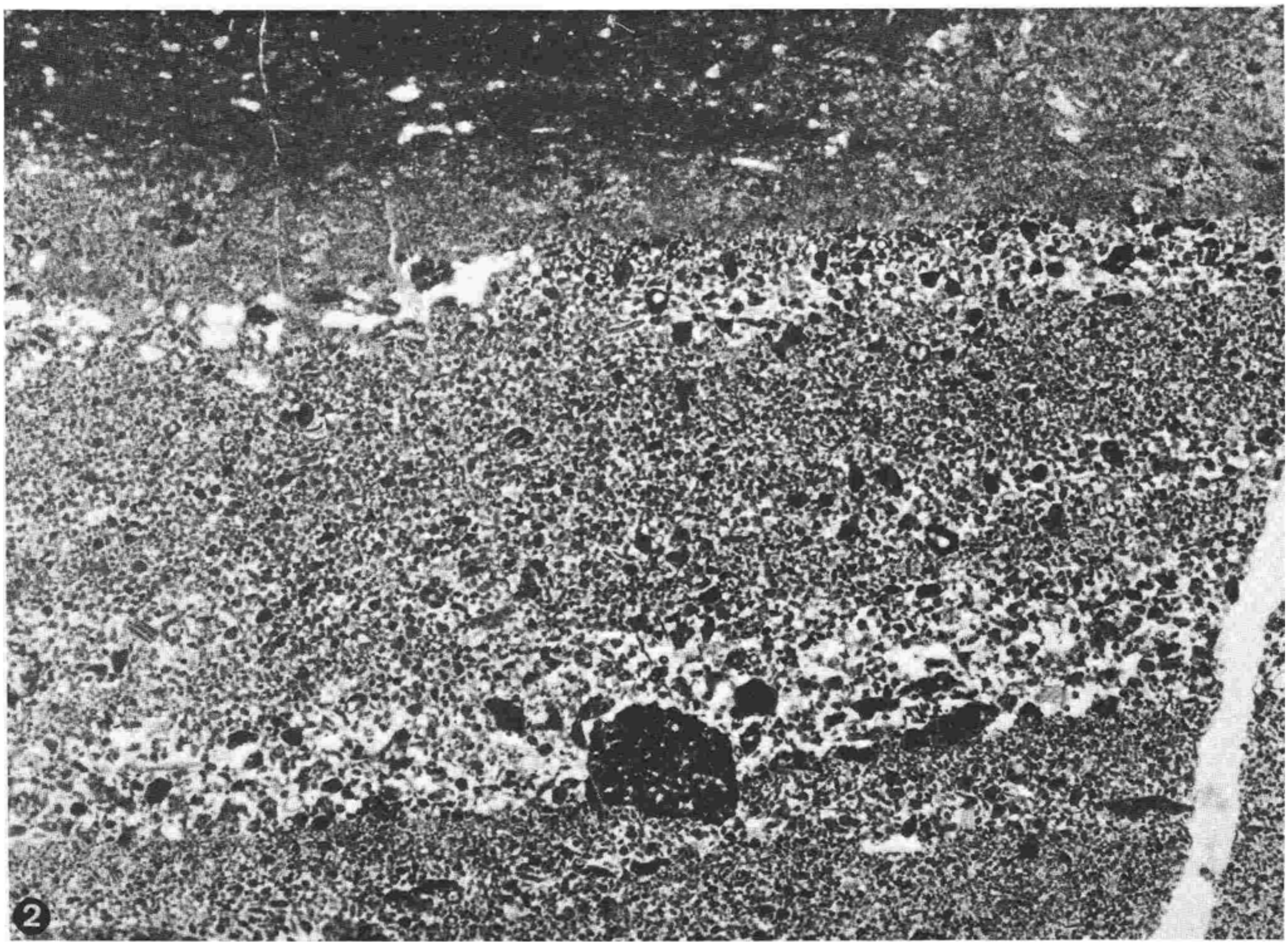

Plate 9

Development of Middle and Upper Devonian Buildups
Microfacies Association L

Fig. 1. Poorly washed biosparite with cephalopods and other pelagic fossils. Upper Frasnian: Horni Benesov ore mines Microfacies association L. x 6.2

Fig. 2. Biomicrite to fossiliferous micrite with clay admixtures; scattered Solenoporaceae indet., ostracods, porifera,spicules, crinoid ossicles. Upper Famennian: foraminifer zone *Quasiendothyra* "no. 5" (J. KALVODA, personal communication). Uhrice 7 borehole, core no. 10, southeast of Brno, Moravia, Microfacies association L. x 8

Comments: The examples of microfacies associations on the plates are based on samples and/or field sections surveyed by the author. Some of the photographs were taken by V. Kosmák, K. Navrátilová, L. Bláhová, J. Otava, and V. Skala.


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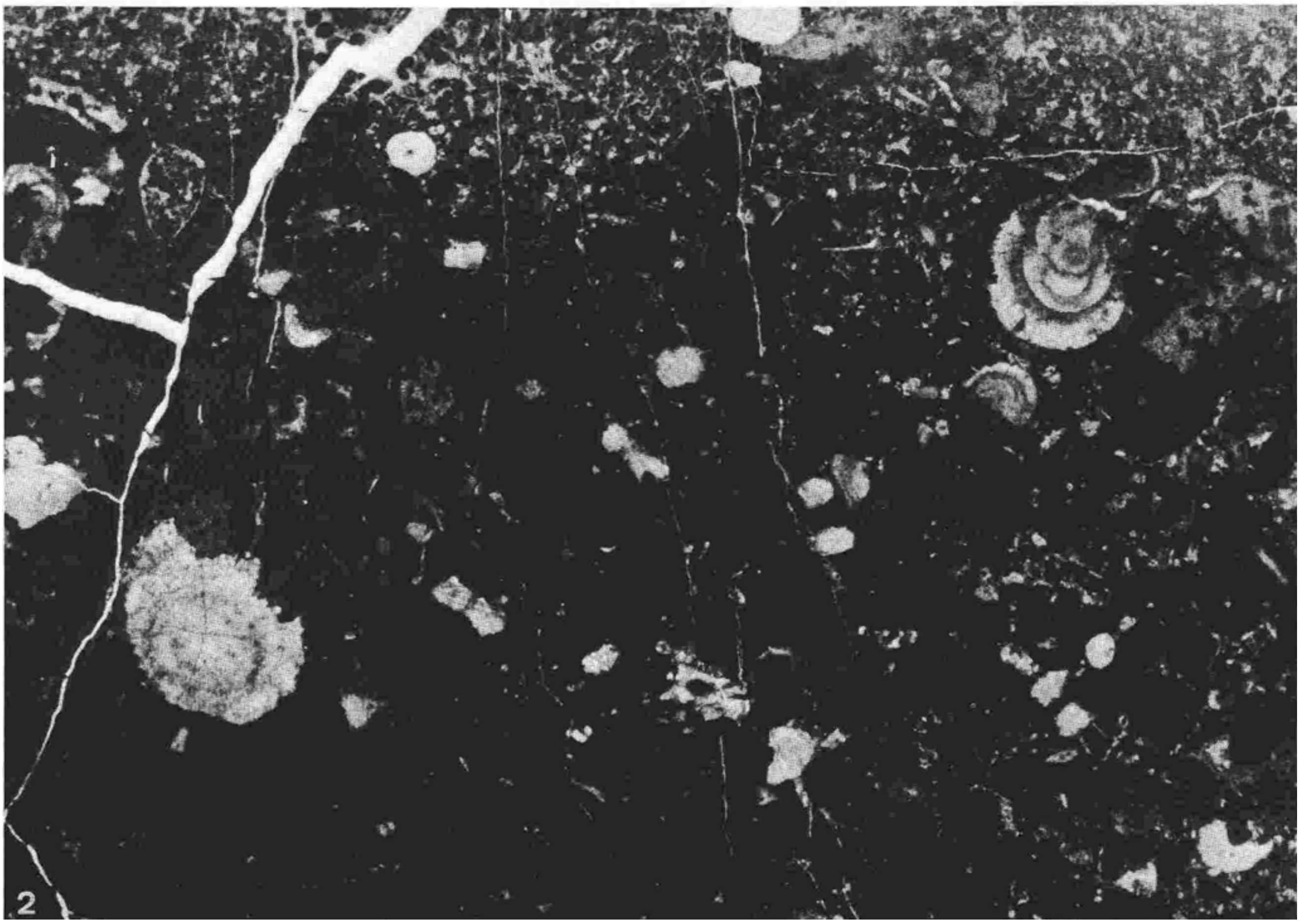
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