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Occurrence and significance of reworked palynomorphs

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ABSTRACT

Palynomorphs are dispersed by wind or water. The number of palynomorphs that eventually is deposited in a certain environment is reduced by oxidation processes during this transport. Even after deposition, their number may be further reduced by oxidation within the sediment.
Post-depositional erosion or mass transport of the sediment in which the palynomorphs have been preserved may rework the same into deposits of a stratigraphically different age. Most commonly, these are reworked into stratigraphically younger deposits.
The occurrence of reworked plant microfossils is considered as mere contamination by some biostratigraphic workers. However, reworked palynomorphs may help to trace tectonic movements. Moreover, they may yield a key for the source area of the sediment in which they have been reworked. Therefore, they are considered as valuable tools for the reconstruction of paleogeographic events.

1. INTRODUCTION

Scanning the literature for papers on reworked palynomorphs necessarily leads to the conclusion that these are far too often considered as a by-product of biostratigraphical research. For example, the only contribution to the "San Francisco Symposium on Palynology in Oil Exploration" (CROSS, ed., 1964a) on this subject mentioned the phenomenon as "contamination in palynology" (CROSS 1964b). Also the special issue "Palynological Contribution to environmental geology" (MANTEN, ed., 1967) includes only one paper dedicating exactly four lines to the record of reworked plant microfossils (HALL & NORTON 1967).

Nevertheless, there exists an extensive literature which proves that reworked palynomorphs are a widespread phenomenon. However, few papers have tried to summarize the palynomorph reworking process (ANANOVA 1960, WILSON 1964, KEDVES et al. 1966, MUIR 1967) and still less have emphasized their great potentiality for paleoenvironmental and paleogeographical applications.

The present report will try to summarize the several aspects of reworking and will be completed by a briefly annotated - although not exhaustive - bibliography.

2. ACKNOWLEDGEMENTS

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3. LATERAL DISPERSAL OF PALYNOMORPHS

Palynomorphs include continentally produced spores and pollen grains as well as one-celled dinoflagellates and acritarchs (presumably representing stages in the life cycles of marine plants).

Spores and pollen grain walls consist of a very refractory C-H-O compound called "sporopollenin" which is practically undestructible. Also dinoflagellates and acritarchs have an organic, very resistant wall. They can only be destroyed by oxidation processes.

Their size matches that of coarse silt particles, but their density is considerably less inasmuch as their organic wall is empty, or - at best - is filled with protoplasm.

Therefore, their hydraulic equivalent is that of particles of a much smaller size. Palynomorphs are produced in tremendous amounts each year, the marine ones since the Pre-Cambrian, the continental ones since Silurian time.

3.1. WIND TRANSPORT

Wind transport of pollen and spores from the plant into the surrounding environment is a penecontemporaneous process. In general, dispersal is restricted to relatively short distances, most pollen being deposited within a few kilometers. Long distance transport by wind is known to occur but apparently it is exceptional.

Depending on atmospheric circulation, coastal pollen rain has sometimes been estimated to range from 100 to 1000 grains/cm^2/year (DYAKOWSKA 1948). The rate of pollen accumulation in lacustrine environments is comparatively high. Local variations between 1000 and 40.000 grains/cm^2/year are known (DAVIS 1967).

3.2. FLUVIAL TRANSPORT

Fluvial transport is probably the major means of spores (often produced by smaller plants) and pollen dispersal into lacustrine, lagoonal and marine deposits (MULLER 1959). It has been proven, that locally more than 90% of the pollen assemblage had been supplied by stream transport (PECK 1973).

The travel time from their source (the area of the parent plants) towards the mouth of a river can be very long, since they are transported over some distance, temporarily deposited and retransported again several times. This intricate process results in a homogeneous mixture of grains from different sources (JONES 1958). Therefore, the pollen spectra of suspended sediments (500 to 8000 grains/liter of water in the Deleware Estuary, U.S.A.; GROOT 1966) are similar to those of the bottom sediments in a river. Both spectra reflect the regional vegetation of the area drained by the river system rather than local plant communities. This becomes particularly true downstreams for the estuarine environment (GROOT 1966).

3.3. MARINE TRANSPORT

The relative amount of pollen and spores occurring in marine sediments depends on many factors (BOTTEMA & VAN STRAATEN 1966). It is often supposed that it decreases considerably with increasing distance to the coast (MULLER 1959). However, sometimes an increase is observed within a few to more than hundred kilometers from the shoreline (STANLEY 1965b).

Dinoflagellates and other presumably marine planktonic forms such as acritarchs may also show an increase of their absolute frequencies with increasing distance from the shoreline with a maximum in slope-rise zone deposits (WALL et al. 1977). The relative or absolute frequency of dinoflagellates and acritarchs is influenced by their depence on special marine environments and hydrodynamic behavior in the sea water. This influence seems to be quite different for different morphological types (WILLIAMS & SARJEANT 1967).

Marine currents are the main agent of transport in oceans and seas. These mix continental and marine palynomorphs. Differences in the relative energy level of the environment may produce more local, size-sorted assemblages.

3.4. OXIDATION

Eventually, the number of palynomorphs decreases. Normally, only relatively few grains are deposited in basinal environments (KORENOVA 1957). This is probably due to the decomposition of the palynomorph grain - caused by oxidation during transport. BRUSH (1966) suggested that also an environment of reducing conditions and high pH may be responsable for the absence of pollen from apparently favourable sediments. As already stated above (3.2.), the grains may be deposited and transported several times. During that period they are exposed to oxidation processes of the water environment. Even if the grain has reached its final deposit, it may take a relatively long period before enough sediment has been accumulated on the grain to protect it from this oxidizing environment. Examples are so-called "relic sediments" (EMERY 1968), which have been recognized at a depth of 150 m on the continental platform east of the U.S.A. and which are about 15.000 years old (EMERY & GARRISON 1967).

4. REWORKING OF PALYNOMORPHS

Under the term "reworking" we understand the reworking of palynomorphs into sediments of a stratigraphically different age. In practice, this may result in a mixed assemblage of palynomorphs of different ages or - in rare cases - the age of the palymorph assemblage is completely different from the sediment in which it has been reworked.

We will exclude artificial mixing due to deficient collecting or processing techniques (WILSON 1964), as well as contamination of cuttings or drilling mud in a borehole (TRAVERSE et al. 1961).

4.1. REWORKING INTO OLDER DEPOSITS ("STRATIGRAPHIC LEAKAGE")

Downwashing of palynomorphs in fissures or cavities of a karstified rock is easily recognized. Examples are modern pollen in Mississippian Limestone of northwestern Kansas, Pennsylvanian spores and pollen in Devonian Limestone of Illinois, Iowa and Missouri, Devonian spores in Silurian reef limestone of Illinois (GUENNEL 1963, WILSON 1964, UPSHAW & CREATH 1965).

Spores and pollen grains may be downwashed from a sandy soil into underlying deposits (DIMBLEBY 1957). The recognition of this process was used by MUNAUT (1967) in his research on Quaternary paleoecology.

BASTIN (1971) has shown that *Lombricides* (worms) transported Holocene pollen into the uppermost part of a Pleistocene loess.

AKYOL (1975) describes contamination of Lower Permian rocks in Sariz (Turkey) by Jurassic palynomorphs which had been transported by a recent fluvial system. Maybe these Jurassic palynomorphs have been downwashed into open joints or fissures of the Permian rocks?

Downwashing of palynomorphs into older deposits should be distinguished from cases where apparent guide fossils turn out to have a much earlier "first occurrence" in the geological history. An example of the latter was described by BLESS et al. (1977) from the Upper Westphalian C of Haaksbergen (the Netherlands). They observed several spore species in strata of a proven Westphalian C age which up to then had been considered characteristic for Stephanian or even younger sediments. This surprising find was ascribed to a special hinterland facies.

4.2. TECTONIC MELANGE

This is a relatively rare case where allochthonous blocks of diverse sedimentary and stratigraphical units are mixed by intricate tectonic movements. The Franciscan Rocks - on which San Francisco, California, is built — contain a melange of palynomorph assemblages of transitional Jurassic/Cretaceous, Upper Cretaceous and late Paleocene age (TRAVERSE 1972, 1976).

4.3. REWORKING INTO YOUNGER DEPOSITS

At some places, spores might have migrated upwards into younger sediments via transport by formation water, oil or gas (DE JERSEY 1965, GROSSGEYN 1971, 1973).

In normal cases, however, reworking into younger deposits is attributed to erosion/denudation of rocks in a source area and subsequent redeposition in a different sedimentation area. This reworking process will constitute the main topic of this paper.

The criteria for recognizing such reworked palynomorphs will be discussed in chapter 5.. These criteria apply, of course, also to the less frequent cases of mixed assemblages mentioned above as well as to cases where the entire microflora consists of reworked palynomorphs (cf. FUNCKHAUSER 1964, OWENS 1972, WILSON 1964).

5. RECOGNITION OF REWORKED PALYNOMORPHS

If we consider the fact that most palynomorph grains are subject of an intricate process of repeated transport and deposition, we must presume that most fossil palynomorphs are allochthonous. This is particularly obvious for pollen and spores found in marine or desert sediments which could not have been produced in such environments (ROSSIGNOL et al. 1979). But even peat (DAVIS 1961) and other swamp deposits (BIRKS 1970, CUSHINC 1964) - particularly in coastal environments - hardly escape lateral contamination (the "incursion phase" of SMITH 1962).

Also marine palynomorphs will rarely fossilize exactly on the place where they had been originally deposited on the sea floor. Some slope-rise assemblages from the Mediterranean and Caribbean seas include "secondary" elements which are interpreted as allochthonous (due to displacement of shallow-water organisms into offshore sediments). These might also represent redeposition from older estuarine-neritic sediments into the outer continental shelf and slope zones (WALL et al. 1977).

In a strict sense, the transport of palynomorphs from one sediment trap into another is a reworking process. In that strict sense, we may consider also the mixing process of palynomorphs from different sources - so helpful for biostratigraphic interpretations - a reworking phenomenon.

In practice, however, the term "reworked" is restricted to these palynomorphs which can be distinguished as being stratigraphically older (or younger) than the deposit in which they occur. This difference in stratigraphic age may be very small and only detectable by special methods or indirect deduction.

— The most sophisticated method is certainly the fluorescence microscopy (VAN GIJZEL 1967). The fluorescence of pollen and spores changes in colour from blue to red and decreases in intensity with increasing age. No special equipment has necessarily to be used for determining the fluorescence colours and intensities, because these can be determined by eye if only obvious differences are accepted as significant (PHILLIPS 1972).

— Plant microfossils of different ages may show a different acceptance to biological staining (staining method of MULLER 1959, STANLEY 1965a, 1966b). Usually, safranin-0 is used.

— Differences in the specific density of the exine of a palynomorph are caused by differences in age as has been shown by JUVIGNÉ (1973).

These methods are usually only successfully applied to Quaternary and Tertiary material.

Indirect deduction that reworked palynomorphs are present has been used in the following examples:

— Abnormal variations in the quantitative distribution of species with a well-known distribution pattern (e.g. if such a species serves as a guide for special climates in Holocene or Pleistocene deposits) have been interpreted as being caused by reworking (IVERSEN 1936).

— Statistic association of a species with known reworked material (SCHUMACKER-LAMBRY 1978), e.g. associated with a well-known reworked fossil, with reworked clay minerals or in reworked rock pebbles (flints, coal, clay clasts).

— Repeated occurrences with coarse detritic sediments (VENKATACHALA 1969).

— Incompatibility of the presumed paleoecological dependence of a microfossil with the paleoenvironment of the sediment in which it is found. *Lycospora* was suggested by PEPPERS (1964) to be possibly reworked in the highest parts of the Upper Pennsylvanian in the U.S.A., where this genus is restricted to clastic deposits. PEPPERS argumented that this genus is only autochthonous in coals of the underlying sediments (from where it was dispersed laterally into the envelopping clastic sediments). However, in the highest Pennsylvanian coals the genus doesn't occur. Therefore it might have been reworked into these highest Pennsylvanian clastics from the still unconsolidated older Pennsylvanian strata.

The same argument may be used if the occurrence of a species is in contradiction with the normal pattern of lateral dispersal (e.g. if marine microfossils are preserved in non-marine sediments), it seems more logical to believe that these are reworked rather than to presume that they were introduced by an incursion of the sea (cf. WILSON 1964, RICHARDSON & RASUL 1978, VANGUESTAINE 1979).

The difference in stratigraphic age may be obvious if the age of the sediment in which the reworked fossil occurs is clearly different from the known range of the latter.

KEDVES et al. (1966) distinguish four categories of reworking:

— simple: sediment contains one single reworked assemblage of one single "age"

— complex: sediment contains two or more reworked assemblages (WILSON 1964)

— primary: one or more assemblages were reworked directly into the sediment from their original deposit(s)

— secondary: the reworked material was reworked two or more times into different deposits before it was finally sedimented in the strata in which it is recognized nowadays (STAPLIN 1969, BIRKS 1970, ZAGWIJN & VEENSTRA 1966, SCHUMACKER—LAMBRY 1978).

A particular case of reworking is the "geological age inversion" of reworked fossils (WILSON 1964, STANLEY 1966b), which may be explained by a gradually deeper cutting erosion in the source area. In that case, the stratigraphically youngest reworked fossils occur in the oldest beds, whereas the stratigraphically oldest reworked fossils (which were derived from the source area when the erosion reached the deeper and older stratigraphic deposits) occur in the youngest beds (fig. 1).

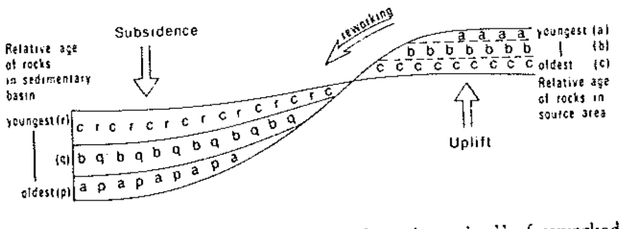

Fig. 1. Simplified example of "geological age inversion" of reworked fossils (dated as a, b, c) due to gradually deeper cutting erosion in source area.

Indirect methods for the recognition of reworked palynomorphs of rather different age can also be used:

— Differences in the coalification degree of palynomorphs usually reflect differences in age. Most curiously, coalified spores may be more resistant to reworking (weathering, transport) than non-coalified specimens (MULLER 1959, MUIR 1967, GRAY & BOUCOT 1975). Differences in the degree of coalification are reflected in difference in the colour of the palynomorphs (STAPLIN 1969, GRAY & BOUCOT 1975).

— Plant microfossils of different ages may be distinguished by their differential preservation. Within each group of organisms, certain morphological structures are destroyed at a different rate (WILSON 1964, WILLIAMS & SARJEANT 1967, FUNKHAUSER 1969).

—An exceptional case was deswcribed by WINDLE (1979), who observed that in some Jurassic deposits the contemporaneous Jurassic megaspores could be distinghuished from reworked Carboniferous megaspores by a differential compression of the spore-wall.

5.1. CLASSOPOLLIS

Classopollis is an easily distinguished pollen grain, frequently dispersed in tetrads, which is extremely abundant in Jurassic deposits. It is easily recognized in reworked pollen assemblages (recorded in 16 papers reviewed in this report).

Classopollis was also common in the early Cretaceous of lower paleolatitudes where their parent plants must have been predominant in some equatorial areas, where they died out in late Cenomanian time (COUPER 1964, HUGHES 1976).

Classopollis has been mentioned from the Upper Cretaceous of North America by several authors, but was rarely recognized as a reworked form derived from older deposits (cf. NORTON & HALL 1967). But nowhere, *Classopollis* was recognized in Upper Cretaceous sediments in the enormous quantities that were observed in the Upper Maastrichtian near Maastricht, where many samples from the basal portion of the Vylen Limestone (''Craie grise'', lowest member of Gulpen Formation) in the North and Hallembaye Quarries (NE Belgium) yielded up to 100 grains per gram of sediment (VANGUESTAINE 1966). The Vylen Limestone is a transgressive unit overlying the Campanian ''Zeven Wegen Limestone'' (''Craie blanche''). Associated with high numbers of extant dinoflagellates we distinguish three groups of pollen and spores, of which at least two have been reworked:

— bisaccate and porate pollen
— *Classopollis* and *Zonalapollenites*
— badly preserved spores amongst which *Lycospora* and *Densosporites*

Bisaccate and porate pollen were linked to the silty fraction of the sediment (VANGUESTAINE 1966). They might be reworked. But we assume that the large amount of *Classopollis* is better explained by accepting that these pollen grains were reworked from Jurassic or Lower Cretaceous sediments. A possible source area might be the western part of the Roer Valley Graben which was uplifted by inverse movements during the Upper Cretaceous. The specimens of *Lycospora* and *Densosporites* may have been derived from Carboniferous outcrops in South Limburg (the Netherlands).

5.2. SPELAEOTRILETES LEPIDOPHYTUS

Spelaeotriletes lepidophytus is restricted to the uppermost Devonian (uppermost Famennian or Strunian). The species is quite abundant in deposits of this age across the world and can easily be distinguished by its morphology. It is also readily recognized in reworked spore assemblages. We found seven records in the literature.

We presume that *S. lepidophytus* has been recognized in younger stratigraphic units, but incorrectly was assigned to other (new) taxa.

Discontinued ranges of a species are often good arguments for the recognition of reworked palynomorphs. WINDLÉ (1979) has shown that frequently two possible solutions are choosen:

— The spore is correctly identified and the ''range'' of the species is extended.
— The reworked species is not correctly identified and assigned to other (often new) species.

In contradiction with the former opinion expressed by one of us in OWENS & STREEL (1967), *Hymenozonotriletes molestus* and *H. mentitus* from Visean deposits of the Dnieper-Donetz Basin (U.S.S.R., ISCHENKO 1958), as well as *Retispora florida* from the Visean strata of Alberta, Canada (STAPLIN 1960) should be considered as reworked specimens of *S. lepidophytus* derived from uppermost Famennian sediments.

The two specimens of *Endosporites lacunosus* from the lower part of the Tournaisian (Cuyahoga Formation) in Ohio (U.S.A., WILSON 1962) may also be reworked specimens of *S. lepidophytus*.

A special case is the occurrence of *S. lepidophytus* in the Hangenberg Shales (Hönnetal area, Rhenish Massif, Germany) which may be partly due to reworking.

The Hangenberg Shales are deep-water deposits irregularly intercalated in between Devonian and Dinantian cephalopod limestones. The age of these shales is post-Tn1a (dated by PAPROTH & STREEL 1971 by means of independent arguments). They contain large amounts of *S. lepidophytus* with size characteristics corresponding to those of mixed Fa2d to Tn1a populations. We believe that this assemblage belonged to a relatively nearshore (no marine acritarchs occur!), shallow water sediment of Fa2d/post-Tn1a age which was introduced into the basin by mass-gravity transport during the post-Tn1a.

6. ANNOTATED LIST OF REWORKED PALYNOMORPH OCCURRENCES

Some 100 cases of reworked palynomorphs are reviewed below, of which 36 refer to Quaternary deposits. They are listed according to the depositional environment in which they have been redeposited. These environments range from lacustrine to deep-sea sediments. For a more detailed description of the cases mentioned below, the reader is referred to the original papers.

6.1. LACUSTRINE AND PEAT DEPOSITS

— Permian pollen and spores in Tertiary lignites of northern Kerala, southern India (POTONIÉ & SAH 1960, VENKATACHALA 1969)

— Up to 60% of Mesozoic and Cenozoic spores, pollen (including *Classopollis*) and dinoflagellates in late glacial (Bolling to Allerød) sandy facies with clay flakes ("galets mous") in lacustrine deposits near Friburg, Switserland (JAN DU CHÊNE 1975)

— A few "pre-Quaternary" pollen (including *Classopollis*) and spores (distinguished as reworked by fluorescence microscopy) in three Pleistocene samples from Lincolnshire and Nordfolk, Great Britain (PHILLIPS 1972)

— Cretaceous pollen, spores and dinoflagellates in late-Wisconsin silty deposits of Glacial Lake Grantsbury, east-central Minnesota, U.S.A. (CUSHING 1964)

— Up to 40% unidentified reworked pollen and spores (distinguished only by staining method) in Albian(?) coals of northern Alaska (STANLEY 1967a)

— Late Cretaceous to Tertiary pollen in basal silty portion of late glacial peat bog near Taunton, Massachusetts, U.S.A. (DAVIS 1961)

— Tertiary pollen and dinoflagellates in late glacial minerogenic sediments of Denmark (IVERSEN 1936)

— Miocene pollen in "diluvial" peats of Silesia, Poland (KRÄUSEL 1922).

6.2. FLUVIATILE TO SHALLOW MARINE ENVIRONMENTS

— Tremadocian and Wenlockian acritarchs in Lower Devonian (Old Red Sandstone) deposits of Wales, Great Britain (EDWARDS et al. 1978, THOMAS 1978)

— Tremadocian, Ordovician and Silurian acritarchs in Emsian (Old Red Sandstone) deposits in Witney borehole, Oxfordshire, Great Britain (RICHARDSON & RASUL 1978)

— Tredadocian and Middle to Late Silurian acritarchs in Dinantian strata of Ireland (SMITH 1977)

— Ordovician acritarchs in Llandoverian, Wenlockian and Ludlovian strata south of the Brabant Massif, Belgium (MARTIN 1969, 1974)

— Ordovician and Silurian acritarchs in Siegenian and Emsian epicontinental deposits, Dinant Nappe, Belgium (VANGUESTAINE 1979)

— Mississippian shale with Devonian spores overlain by Mississippian shale with Ordovician acritarchs and chitinozoa in Oklahoma, U.S.A. (WILSON 1964). This phenomenon is called here "geological age inversion" (fig. 1) and suggests gradually deeper cutting erosion in source area

— Ordovician acritarchs, Devonian, Mississippian and partly Pennsylvanian pollen and spores in Pennsylvanian of southern Oklahoma, U.S.A. (WILSON 1964, 1965)

— Silurian(?), Lower Devonian and Lower Famennian acritarchs in uppermost Famennian marine sediments of eastern part of Dinant Nappe, Belgium (VANGUESTAINE 1978)

— Generally unidentified pollen and spores (distinguished only by staining method) in Quaternary clays from bottom core (length of core: 5.6 m) of southwestern Atlantic continental platform (water-depth 70 m). Reworked sporomorphs make up 30% of microflora (STANLEY 1967b)

— Up to 40% of Paleozoic to Mesozoic spores and pollen (including *Classopollis*) and a few Tertiary pollen in three Holocene bottom cores (length 1 m) of Outer Silver Pit area (North Sea, water-depth 54 to 80 m). Assemblage presumably derived from now submerged Pleistocene boulder clay in same area which originated from British Isles (ZAGWIJN & VEENSTRA 1966)

— Reworked miospores (age unknown) in Permian and Triassic sediments of Pechora Basin, U.S.S.R. (VIRBITSKAS & KHAYTSER 1977)

— Paleozoic pollen and spores in late Cretaceous sediments of eastern Montana, U.S.A. (HALL & NORTON 1967)

— Generally unidentified reworked pollen and spores (distinguished by staining method) in Holocene/Pleistocene clays from four cores (0.6 to 46 m in length) taken from bottom sediments at depths between 18 and 165 m of the northeastern Atlantic continental platform (STANLEY 1966a). In the longuest core (46 m), reworked microfossils occur in the following order: Lower Tertiary forms occur in the lower part of the core, Mesozoic palynomorphs (including *Classopollis*) in the middle part, and Paleozoic microfossils in the upper part of the core. This phenomenon is called here "geological age inversion" (fig. 1) and suggests gradually deeper cutting erosion in source area (STANLEY 1966b, GROOT & GROOT 1964)

— Devonian and Dinantian spores in Lower Permian of Yukon Territory, Canada (BARRS 1967)

— Middle Devonian spores in Westphalian C non-marine deposits of Neeroeteren borehole, northeastern Belgium (STREEL in: BLESS & STREEL 1976)

— Upper Givetian to Middle Frasnian spores (up to 50% of palynomorph assemblages) in late Frasnian to Famennian evaporitic deposits in southern Pripyat Depression, U.S.S.R. (KEDO et al. 1975)

— Some 50 species of Middle Devonian to Lower Westphalian spores (including *S. lepidophytus*) and acritarchs (up to 2.5% of total microflora) in Westphalian C non-marine sediments of Jabeek borehole, South Limburg, the Netherlands (BLESS & STREEL 1976)

— Upper Devonian, Tournaisian and Visean sporomorphs in Visean deposits of Swiebodzice Depression, Poland (KRAWCZYNSKA-GROCHOLSKA 1973)

— Upper Devonian megaspores in red and grey Early(?) Triassic muds, Meville Island, Arctic Canada (HILLS & WALLACE 1970)

— Famennian (including *S. lepidophytus*), Dinantian and Triassic pollen and spores, Jurassic and Cretaceous pollen, spores and dinoflagellates (up to 30%) in Upper Paleocene estuarine to lagoonal deposits of Naheola Formation of southwestern Alabama, U.S.A. (MCLEAN 1968)

— Uppermost Devonian (including *S. lepidophytus*) miospore assemblage in Permo-Triassic beds (without other plant microfossils) overlying Permo-Triassic beds with Upper Carboniferous spores in South Devon (Exmouth Sandstone and Mudstone Formation), Great Britain OWENS 1972). This sucession is interpreted here as "geological age inversion" (fig. 1) and suggests gradually deeper cutting erosion in source area

— Carboniferous spores in Rhaeto-Liassic deposits of Democratic Republic of Germany (SCHULTZ 1967)

— Carboniferous *Lycospora*(?) in Rhaeto-Liassic of southern Sweden (NILSSON 1958, WINDLE 1979)

— Carboniferous mega- and miospores in Rhaeto-Liassic of southeastern Luxemburg (HAGEMANN 1967)

— Carboniferous mega- and miospores in Lower Liassic of southern Denmark (BERTELSEN & MICHELSEN 1970, LUND 1977)

— Carboniferous miospores in Liassic strata of Yorkshire, Great Britain (WILKINSON 1975)

— Carboniferous miospore (*Tripartites trilinguis*) in Upper Liassic of Baltic part of U.S.S.R. (VIENOZINSKIENE & VASISEVA 1971)

— Carboniferous spores in Liassic plant-bearing clays of Grojec near Krakow, Poland (MUIR 1967)

— Carboniferous spores in Liassic of Luxemburg (HILTMANN 1967)

— Carboniferous mega- and miospores and pollen in Liassic (WINDLE 1979) and Lower Kimmeridgian (Upper Jurassic) of northeastern Scotland (LAM & PORTER 1977)

— Carboniferous miospore (*Tripartites trilinguis*) in Middle Jurassic of southern Sweden (GUY 1971, WINDLE 1979)

— Carboniferous megaspores in Middle Jurassic sands of Oxfordshire, Great Britain (WINDLE 1979)

— Carboniferous spores in marine Paleocene strata of Arkansas, U.S.A. (WILSON 1964)

— Lower Pennsylvanian or possibly Mississippian spores in Tertiary silty shales of Wyoming, U.S.A. (WILSON 1964)

— Carboniferous and Rhaetian pollen and spores in Liassic of eastern Netherlands (HERNGREEN & DE BOER 1974)

— Carboniferous spores in coal pebbles reworked into Cretaceous flysch deposits of Carpathians (HAVLENA 1956, TURNAU 1962, 1970, ZERNDT 1932)

— Carboniferous and Mesozoic pollen and spores in Holocene salt marshes (surface samples) of Norfolk, Great Britain (RUTHERFORD 1975)

— Eocene Green River deposits containing Upper Cretaceous pollen and spores, overlain by deposits of same age with Middle to Upper Mesozoic pollen and spores overlain by beds of same age containing Upper Paleozoic pollen and spores in eastern Utah, U.S.A. (STANLEY 1966b). This succession suggests "geological age inversion" (cf. fig. 1), due to gradually deeper cutting erosion in source area

— Lower Namurian spores in reworked coal pebbles occurring in Westphalian B-C beds of non-marine Upper Silesian Coalfield, Poland (DEMBOWSKI & JACHOWICZ 1964)

— Westphalian B-C miospores in coal pebbles reworked into Neocomian (Wealdian) deposits of Lower Saxony, Federal Republic of Germany (KREMP 1953, POTONIE & KREMP 1955)

— Westphalian B-C megaspores in reworked coal pebbles occurring in Senonian marine limestone of South Limburg, the Netherlands (DIJKSTRA 1950)

— Probably Westphalian megaspores in Eocene plant-bearing sandy deposits of Hampshire, Great Britain (DIJKSTRA 1950)

— Permian pollen and spores in Upper Jurassic deposits, Kutch, India (VENKATACHALA 1969)

— Permian pollen and spores in Lower Cretaceous deposits near Sehora, Madhya Pradesh, India (DEV 1959, VENKATACHALA 1969)

— Permian and possibly Triassic miospores in mostly marine carbonaceous sediments ranging from Upper Cretaceous to Eocene in Victoria, Australia (COOKSON 1955)

— Permian, Mesozoic (including *Classopollis*) and lower Paleocene pollen and spores in late Miocene (Upper Pannonian) beds of Hungary (KEDVES et al. 1966). These authors studied 803 samples from four cores!

— One early Mesozoic spore species and perhaps a pollen species in coarse clastic deltaic sediments of Middle Jurassic age of Yorkshire, Great Britain (MUIR 1967)

— Buntsandstein dinoflagellates, Cretaceous, Paleocene and Upper Eocene spores, pollen and dinoflagellates in Lower and Upper Oligocene molasse deposits of Inn Valley, Bavaria, Federal Republic of Germany (SCHNABEL & DRAXLER 1976)

— Mesozoic to Pleistocene dinoflagellates, spores and pollen (up to 13%) in (late Pleistocene?)-Holocene deposits of the Black Sea floor near Danube Delta (ROMAN 1974). Reworked palynomorphs were recovered from 3 cores.

— Rhaeto-Liassic palynomorphs in early Cretaceous deposits of Svalbard (SMITH et al. 1976)

— Liassic and later Jurassic pollen, spores and atritarchs from terrestrial to marginal marine sediments reworked into more marine Callovian (Middle Jurassic) deposits of Yorkshire, Great Britain (MUIR & SARJEANT 1978)

— *Classopollis* and other Jurassic palynomorphs in lagoonal to estuarine Paleocene ("Sparnacian") Woolwich Beds of Kent, Great Britain (GRUAS CAVAGNETTO 1970)

— Jurassic spores and pollen (including *Classopollis*) in Paleocene and Eocene clays (Ypresian, Landenian) of Compiègne, northeastern France (KEDVES 1967, 1968)

— Jurassic spores and pollen (including *Classopollis*) in early Tertiary deposits (without extant sporomorphs!) of western Scotland (PHILLIPS 1974)

— Jurassic pollen in Tertiary deposits of Tian Chan, Kazachstan, U.S.S.R. (BARBASINOVA & PIGULOVSKIJ 1953)

— Middle to Upper Jurassic and Lower Cretaceous spores, pollen, dinoflagellates and acritarchs (the latter making up to 17%) in Eocene London Clay of southern England (WILLIAMS 1963)

— Upper Jurassic (Kimmeridgian) spores, pollen (including *Classopollis*) and some dinoflagellates in Eocene (Ypresian) marine sands and clays near Bray, northern France (CAVELIER & CHATEAUNEUF 1971)

— Upper Jurassic dinoflagellates in Eocene of West Pakistan (SARJEANT in: WILLIAMS & SARJEANT 1967)

— Cretaceous palynomorphs in Paleocene deposits of Colorado, U.S.A. (NEWMAN 1966)

— Late Cretaceous microfossils in Paleocene Fort Union Formation of Wyoming, U.S.A. (FUNKHAUSER 1969)

— Late Cretaceous dinoflagellates (up to 2%) in Paleocene (Lower Landenian) sediments of Gelinden, Belgium (SCHUMACKER-LAMBRY 1978)

— Upper Cretaceous spores, pollen (including *Classopollis*) and dinoflagellates in bottom sediments of northern part of Gulf of California, Mexico, some 80 km southeast of Colorado Delta (CROSS 1972). Reworked palynomorphs make up to 20% of microflora!

— Late Cretaceous to Eocene pollen, spores and dinoflagellates in Middle Pleistocene deposits of New Zealand (WILSON 1973)

— Latest Cretaceous microfossils in Eocene beds without other microfossils of Venezuela (FUNKHAUSER 1969)

— Early Tertiary pollen and spores in Middle(?) Tertiary deposits near Euskirchen, Federal Republic of Germany (THOMSON 1952)

— Tertiary (and Pleistocene?) pollen grains (up to 17% of total palynomorph sum) in recent delta levee deposits of Orinoco Basin (MULLER 1959)

— Tertiary and Pleistocene palynomorphs (up to 8%) in recent marine bottom sediments of Trinidad. Reworked material derived from Tertiary and Pleistocene cliffs (MULLER 1959)

6.3. RELATIVELY DEEP-MARINE DEPOSITS

— Paleozoic, Mesozoic and Cenozoic spores and pollen from Holocene(?) bottom core of Biscay Abyssal Plain (water-depth more than 4000 m), eastern Atlantic (GROOT 1963)

— Upper Devonian (Tn1a) spores (including *S. lepidophytus*) in uppermost Devonian (basal Tn1b) turbidites of Hönne Valley, Rhenish Massif, Federal Republic of Germany (PAPROTH & STREEL 1971)

— Assemblages of small Upper Carboniferous miospores (poor in species) in thin coal intercalations in Middle Jurassic (Aalenian) flysch of Branisko Series of Pieniny Klippen Belt, Poland; presumably derived from soft coals which easily desintegrated and subsequently were transported from coastal area into basin by turbidity currents together with sand and clay (BIRKENMAJER & TURNAU 1962)

— Pennsylvanian and a few Cretaceous pollen and spores in Pleistocene red deposits in deep continental margin of northwestern Atlantic (waterdepth 455 to 4398 m; NEEDHAM et al. 1969)

— Mesozoic *Ovalipollis* and *Classopollis* in two Holocene(?) bottom cores (length 1 m) of Japanese Trough (water-depth respectively 4500 and 9200 m; BOULOUARD & DELAUZE 1966)

— Up to 3% of Mesozoic to Pleistocene spores and pollen in (late Pleistocene?)-Holocene sediments from one bottom core of Black Sea floor (water-depth about 2000 m), some 150 km east of Bulgarian coast. Also some reworked dinoflagellates were found (ROMAN 1974)

— Up to 15% of Late Cretaceous and Early Tertiary pollen and other plant microfossils in late Pleistocene silts and clays from two complementary bottom cores of Black Sea floor (water-depth more than 2000 m; TRAVERSE 1974)

— Up to 100% of Upper Cretaceous, late Tertiary and presumably Older Pleistocene (recognized only by staining method) plant microfossils in Quaternary clays from two bottom cores (length respectively 8.6 and 9.6 m) of Gulf of Mexico (water-depth respectively 3484 and 3625 m; STANLEY 1966a, 1966b)

— Up to 100% of unidentified reworked pollen and spores (distinguished only by staining method) in Quaternary clays from seven bottom cores (length between 3.9 and 8.7 m) of northwestern Atlantic (water-depth between 1410 and 5508 m; STANLEY 1966a)

— Up to 100% of unidentified pollen and spores (distinguished only by staining method) in Quaternary clays from one bottom core (length 4.8 m) of equatorial Atlantic (water-depth 3320 m; STANLEY 1966a)

— Up to 40% of unidentified reworked pollen, spores and dinoflagellates (distinguished only by staining method) in Quaternary clays from five cores (length 7.4 to 11.9 m) of southwestern Atlantic (water-depth between 3720 to 5885 m; STANLEY 1967b)

6.4. GLACIAL DEPOSITS

6.4.1. *Continental glacial deposits*

— Millions of Devonian *Tasmanites* in recent clays of Lake Michigan near Chicago, Illinois, and Milwaukee, Wisconsin, U.S.A. (JOHNSON & THOMAS 1884, WINSLOW 1962, WILSON 1964). HOUGH (1934) reports that *Tasmanites* (called *Sporangites huronensis* by that author) was even discovered in the Chicago city water supply as early as 1865, long before this species was described from Devonian black shales in Lake Huron

— Coal pebbles with Carboniferous megaspores in glacial deposits near Ann Arbor, U.S.A. (BARTLETT 1928)

— Carboniferous and Jurassic spores in Pleistocene boulder clay near Outer Silver Pit area of the North Sea (grab sample). This boulder clay was presumably derived from British Isles (ZAGWIJN & VEENSTRA 1966)

— Mesozoic spores, pollen (including *Classopollis*) and dinoflagellates in Pleistocene silty clays (reworked from underlying boulder clay) of East Anglia, Great Britain (TURNER 1970)

— Jurassic spores, pollen and dinoflagellates in Late Weichselian limnic clays of Isle of Skye, Great Britain (BIRKS 1970)

— Wealdian, Paleocene, Miocene, Pliocene and Middle Pleistocene pollen and spores in Saalian boulder clay of Scandinavian origin in the Netherlands (ZAGWIJN & VEENSTRA 1966)

— Late Cretaceous to Paleocene pollen and Tertiary(?) dinoflagellate in varved clay near Taunton, Massachusetts, U.S.A. (DAVIS 1961)

— Tertiary pollen and dinoflagellates in Pleistocene boulder clay and varved clay of Denmark (IVERSEN 1936)

— Eemian tree pollen in early Weichselian sandy gyttja deposit near Amersfoort, the Netherlands (ZAGWIJN 1961)

— Interstadial or interglacial marine Pleistocene(?) plant microfossils in tills and glacial silty clays of Cape Cod, Massachusetts, U.S.A. (MATHER et al. 1942, SAYLES & KNOX 1943)

6.4.2. *Marine glacial deposits*

— Permian, early Cretaceous and late Cretaceous/early Tertiary pollen and spores and late Cretaceous/early Tertiary dinoflagellates in nine Holocene(?) samples from Weddell Sea, Antarctica (KEMP 1972a)

— Permian, early Cretaceous (including *Classopollis*) and late Cretaceous/basal Tertiary pollen and spores and Lower Tertiary dinoflaggellates in muds of three Holocene(?) grab samples (one sample containing also pebbles up to 0.5 cm) from West Ice Shelf Sea, East Antarctica (KEMP 1972b)

— Permo-Triassic pollen and spores (and Tertiary? microfossils) in Holocene(?) muds from four grab samples collected from Ross Sea floor (water-depth between 500 and 1300 m), Antarctica (WILSON 1968)

— Upper Cretaceous to Paleocene(?) pollen (transported by icebergs?) in late to post-glacial clays of southwestern Sweden (FRIES & ROSS 1950)

7. AGE OF HOST ROCKS

The ages of sediments containing reworked palynomorphs ("host rocks") are not randomly distributed on the geological scale (fig. 2). Distinct peaks occur in the

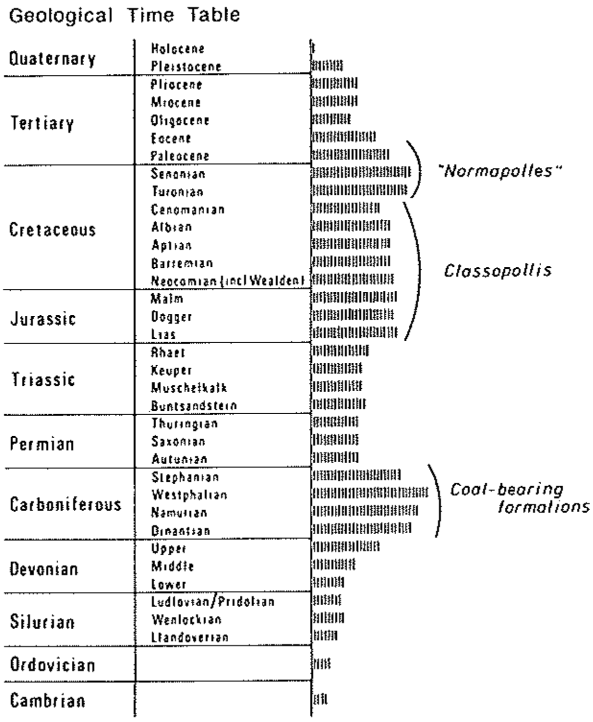

Fig. 2. Correlation between literature records of sediments with reworked palynomorphs ("host rocks") and main orogenic events and Quaternary glaciations and sea level changes.

= Fig. 3

Quaternary, Lower Tertiary, Neocomian, Rhaet/Dogger, Westphalian, late Devonian/Dinantian and Lower Devonian. The fact that these peaks become smaller - and therefore maybe less convincing at first sight - is easily explained, if we consider the circumstance that the number of papers dealing with palynomorphs is much lower for older than for younger deposits.

We do not believe that this curious distribution of the reworked palynomorph record is due to a haphazard literature compilation. This rather suggests that there were periods in history during which the reworking process was intensified by geological phenomena. We presume, that a correlation can be made between these peaks and the main orogenic events inasmuch as Tertiary and older deposits are concerned, and with glaciations and base level changes (sea level changes) during the Quaternary.

7.1. QUATERNARY

Several cases can be correlated directly with glacial phenomena (cf. 6.4.). Many other cases are to be associated with increased erosion during glacial periods (STANLEY 1965a, 1966a). This may be especially true for most of the occurrences in marine environments.

In some sediments, all or practically all plant microfossils seem to be reworked.

In a few cases, the reworked palynomorphs were secondarily derived from glacial deposits into which they had been reworked earlier (ZAGWIJN & VEENSTRA 1966, cf. 6.4.1.).

7.2. LOWER TERTIARY

This peak seems to correspond to molasse deposits related to the Laramian (and maybe late Subhercynian) orogenesis. One of the best examples is from Bavaria (Germany) described by SCHNABEL & DRAXLER (1976).

The percentage of reworked palynomorphs is usually much lower than that in some Quaternary deposits.

7.3 NEOCOMIAN

A barely perceptible peak of reworked palynomorph records may be related to the Late Kimmerian movements. KREMP (1962) summarized several occurrences of reworked plant microfossils from the German Lower Cretaceous.

7.4. RHAET/DOGGER

This distinct peak is clearly related to Early Kimmerian movements. Most of the cases recorded are within the north-European sedimentary area (WINDLE 1979)

7.5. WESTPHALIAN

Reworked palynomorphs were derived from the mobile Variscan /Appalachian belt in NW Europe and North America. All the occurrences are clearly related to Asturian movements which influenced especially the Upper Westphalian sedimentation.

7.6. UPPER DEVONIAN/DINANTIAN

Reworked spore occurrences can be related to the Bretonian orogenesis. Several cases are known that latest Devonian (Strunian) palynomorphs were reworked in the Dinantian.

7.7. LOWER DEVONIAN

Occurrences or reworked palynomorphs in Lower Devonian sediments are restricted to the area south of the Wales-Brabant Massif in NW Europe. These cases are clearly linked to late Caledonian movements.

8. AGE OF PRIMARY SOURCE ROCKS

The age of the primary source rock from which palynomorphs have been derived is frequently poorly defined in literature. In several cases only the occurrence of reworked palynomorphs is mentioned, but no reference to a specific age of the same is given. In other cases, reference is made to e.g. Paleozoic spores or Carboniferous spores.

Exact age determinations are relatively rare.

Therefore, a table with the ages of the reworked palynomorphs as referred to in literature necessarily contains a strong "background noise" that obscures the details (fig. 3). The increase of this background noise into younger stages may be due to the general increase of palynomorphs in younger stages.

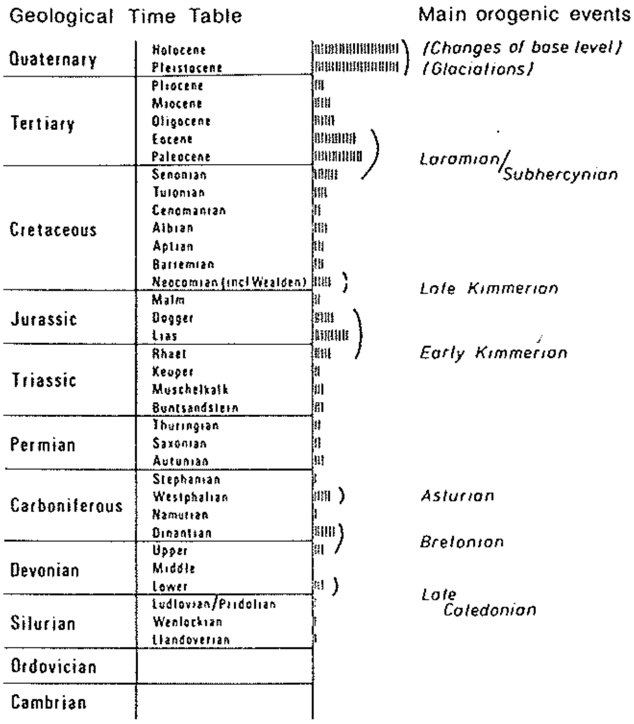

Fig. 3. Literature records of presumable age of reworked palynomorphs.

Fig 2

Three maxima may be distinguished, of which the most obvious one corresponds to the Carboniferous period, the second to the Jurassic/Middle Cretaceous and the third one to the late Cretaceous to Paleocene.

This Carboniferous maximum is easily explained by the extremely prolific vegetation that spread across the earth during the Carboniferous. At many places, repeatedly peat formation occurred. Subsequently, these peats evoluated into partly workable coal seams. Mio- and megaspores (and subordinate pollen) are quite abundant in the coals as well as in many clastic deposits of this period.

In many cases, Carboniferous spores have been recovered from reworked coal pebbles occurring in younger strata. But they may also be found in small reworked shale fragments. In some cases, there are arguments to believe that they occur as single, reworked specimens as well.

The peak for the Jurassic to Cenomanian on figure 2 may be partly explained by the fact that palynomorph assemblages of this age are characterized by the very common and easily recognizable pollen grains of *Classopollis.* It is indeed remarkable, that *Classopollis* is frequently cited in the literature on reworked palynomorphs, even if no other reworked grains are specifically mentioned.

Also the peak for the Turonian to Paleocene may be explained by the fact that palynomorph assemblages of this age include a commonly occurring and easily distinguished group of pollen: "Normapolles".

9. DISTRIBUTION OF REWORKED PALYNOMORPHS

Correlation of the age of the host rocks and the presumed age of reworked palynomorph assemblages seems only justified if the environment of the host rocks is more or less comparable. Analysis of the data in chapter 6 learns that glacial deposits, deep-sea environments or lacustrine to peat bog facies with reworked plant microfossils are practically all - with very few exceptions - of Quaternary age. This is not so surprising since glacial deposits and deep-sea environments of pre-Quaternary age are relatively rarely preserved. This would influence a correlation table in such a way that the figures on the same are no longer comparable.

A second problem is the already mentioned "background noise" produced by inaccurately known ages for host rocks or reworked palynomorphs. We have therefore excluded cases where the age of the host rock is poorly defined (e.g. Cretaceous) or the age of reworked sporomorphs is extremely vague (e.g. Paleozoic to Mesozoic, unidentified).

The remaining cases have been plotted in the correlation table of fig. 4 and refer to reworked palynomorphs in fluviatile to shallow marine sediments of more or less known age.

This table shows five maxima, which correspond to periods characterized by or directly following the main orogenic events of fig. 2. Remarkable is that only the Neocomian peak of fig. 2 cannot be traced in this table.

The first maximum corresponds to Lower Devonian host rocks of the area south of the Wales-Brabant Massif in Wales and Oxfordshire (Great Britain) and Belgium, which contain reworked acritarchs derived from Cambro-Silurian source rocks (in the north the Old Red Continent and in the south the Ardennan massifs) which had been uplifted by late Caledonian movements. VANGUESTAINE (1979) was able to distinguish individual source rock areas because of differences in the regional acritarch assemblages during the Silurian period.

The second maximum corresponds to the Dinantian host rocks of Oklahoma and Ohio (U.S.A.), Alberta (Canada), the northern European sedimentary basin (Ireland, Poland) and the Dnieper-Donetz Basin (U.S.S.R.). Five of the six reworked palynomorph assemblages include sporomorphs derived from Upper Devonian sediments (in three cases including the guide fossil for the uppermost Devonian: *S. lepidophytus;* cf. 5.2.). This suggests that the uplift caused by the Bretonian movements was not very important, because only the youngest deposits were usually removed by the subsequent (Dinantian) erosion.

The third maximum refers to the Westphalian host rocks of Oklahoma (U.S.A.), Poland, northeastern Belgium and the southern Netherlands and can clearly be related with synsedimentary late Variscan/Appalachian movements. The erosion during this period is much more im-

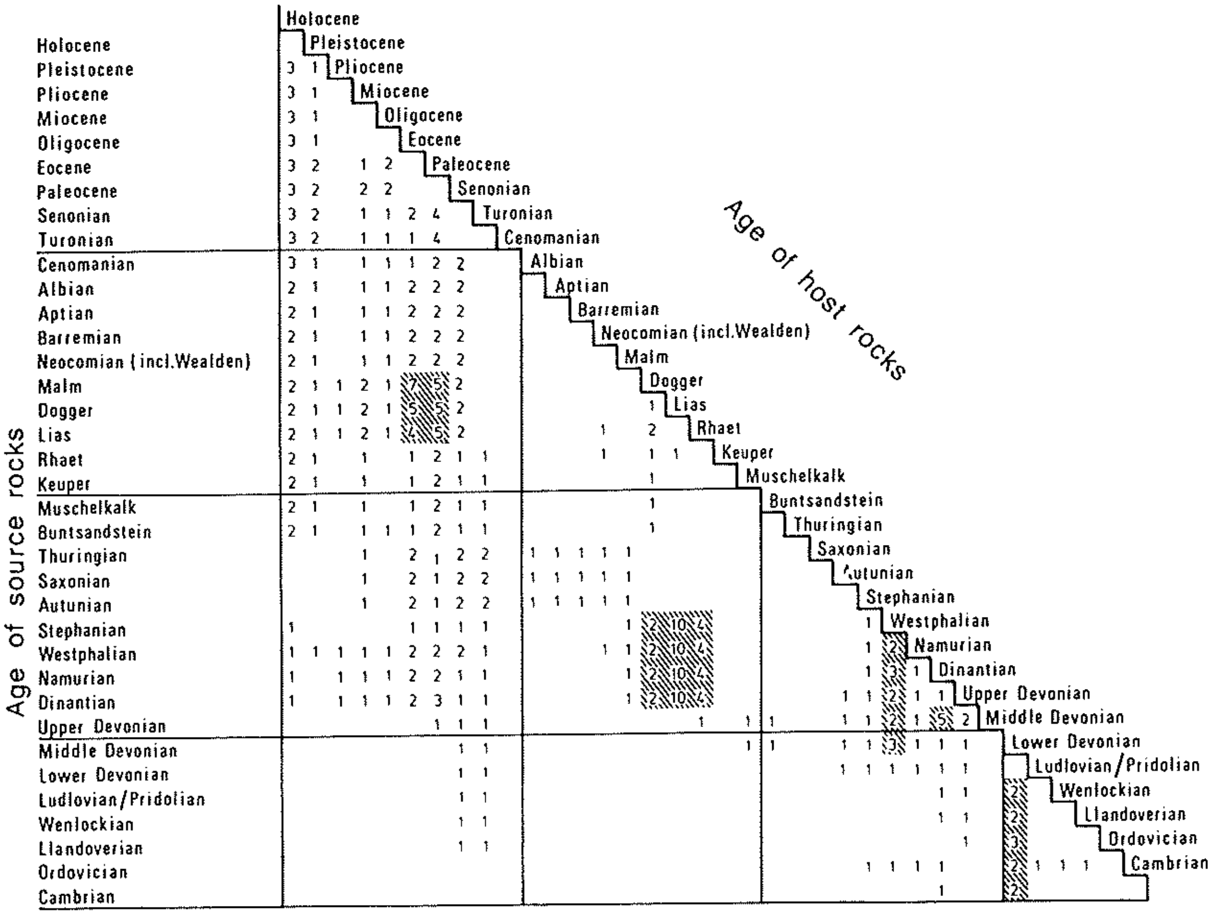

Fig. 4. Correlation between age of reworked palynomorphs and age of host rocks in fluviatile to shallow marine environments.

portant than during the Dinantian as can be deduced from the fact that in three of the four regions Middle Devonian or even older palynomorphs occur in the reworked plant microfossil assemblages. This supports the general impression that late Variscan/Appalachian movements were much more important than the early (Bretonian) movements.

The fourth maximum refers to the Rhaeto-Dogger host rocks of northern Europe (Baltic U.S.S.R., Poland, southern Sweden, Denmark, northeastern Germany, eastern Netherlands, Luxemburg, Yorkshire, Devon and northeastern Scotland) which contain sporomorphs in coal pebbles derived from Carboniferous source rocks. The early Kimmerian movements increased the relative relief in northern Europe. The subsequent Rhaeto-Liassic erosion desintegrated the outcropping Carboniferous coals into small fragments which were easily transported along the margins of the sedimentary basin (cf. WINDLE 1979, fig. 1).

The fifth maximum corresponds to the Lower Tertiary (Paleocene/Eocene) host rocks of W. Pakistan and Kazakstan in Asia, Alabama, Colorado and Utah in the U.S.A., and Scotland, southern England, northern France and northeastern Belgium in northwestern Europe, which contain reworked palynomorphs of preferably Jurassic age. A minor peak can be observed for host rocks of the same age containing reworked Turonian-Senonian palynomorphs (Utah, Wyoming and Colorado in the U.S.A., Venezuela). These occurrences prove the worldwide influence of the late Cretaceous/early Tertiary Alpine movements.

Remarkable is the practical absence of Old Paleozoic palynomorph assemblages in post-Paleozoic deposits. The few exceptions are found in glacial deposits or relatively deep-water marine environments. The apparent occurrence of Old Paleozoic plant microfossils in late Cretaceous sediments of Montana (U.S.A.) is due to the poorly defined age of the sporomorphs (dated as Paleozoic: HALL & NORTON 1967).

Several authors have traced the source areas of the reworked palynomorph assemblages. We may refer to e.g. VANGUESTAINE (1979) for the Ordovician-Sulirian acritarchs in the Lower Devonian of Belgium, BLESS & STREEL (1976) for the Devono-Westphalian palynomorphs in the Upper Westphalian of the southern Netherlands, OWENS (1972) for the Strunian sporomorphs in the Permo-Triassic of Great Britain, SCHNABEL & DRAXLER (1976) for Triassic to Lower Tertiary plant microfossils in the Oligocene of Bavaria, and NEEDHAM et al. (1969) for Pennsylvanian and Cretaceous sporomorphs in Pleistocene red deposits of the northwestern Atlantic. These examples show that reworked palynomorph assemblages may not only reveal the existence of base level changes in a source area (usually due to orogenic movements in pre-Quaternary formations), but also may help to unravel the origin of the sediments in which they occur.

Therefore, systematic description and dating of reworked plant microfossils might yield a valuable contribution to paleogeographic reconstructions. In our opinion, considering reworked palynomorphs as simple contaminations is certainly an undervaluation of a useful component of sedimentary rocks.

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