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THE UNIVERSITY OF ALBERTA

ICHNOLOGY OF THE CARDIUM FORMATION (PEMBINA AREA)

BY

SHAWNA M. VOSSLER

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE.

DEPARTMENT OF GEOLOGY

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled ICHNOLOGY OF THE CARDIUM FORMATION (PEMBINA AREA) submitted by SHAWNA M. VOSSLER in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE.

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ABSTRACT

This study was undertaken to examine the ichnology of the Cardium Formation. This formation has been the focus of much research and controversy in the past, in part because of it's economic importance.

The Cardium Formation is late Turonian in age, and is the middle formation in the Alberta Group. It is found in subsurface throughout western Alberta, where it is comprised of coarsening upward sequences of mudstone and sandstone, which are unconformably overlain by conglomerates or pebble veneers. For this study, 110 core from the Pembina oilfield and the closely associated Carrot Creek oilfield were examined.

The occurrence of a great diversity of ichnogenera was documented in the Cardium. The most common forms were: *Arenicolites*, *Asterosoma*, *Bergaueria*, *Chondrites*, *Conichnus*, *Cylindrichnus*, *Didymaulichnus*, *Diplocraterion*, *Helminthopsis*, *Lockeia*, *Ophiomorpha*, *Palaeophycus*, *Planolites*, *Rhizocorallium*, *Rosselia*, *Skolithos*, *Thalassinoides*, *Teichichnus*, *Terebellina*, *Zoophycos*, and assorted fugichnia.

These ichnogenera occur in seven distinct ichnofossil assemblages which can be correlated to recurring lithofacies identified in the Raven River Member of the Cardium Formation. The ichnology and sedimentology of the Raven River Member support an offshore storm dominated interpretation. Several small coarsening-upward sequences coalesce to form an overall shoaling upward sequence. Sea level fluctuations due to tectonic and possible eustatic causes have been interpreted as the generators of these sequences.

A conglomerate unconformably overlies the fine sandstones and mudstones of

the Raven River Member. This conglomerate along with the overlying mudstone comprise the Carrot Creek Member in the study area. Conglomerate deposition may be linked to a significant lowering of sea level. The unconformity has a locally developed firmground ichnofauna of *Thalassinoides* and *Skolithos*. These burrows were excavated in a nearshore marine setting prior to conglomerate deposition; at this time substrates were semicohesive but unlithified. Firmground recognition in the Cardium Formation and other deposits may be of benefit in the application of sequence stratigraphic principles.

The Cardium Formation in the study area has frequent sharp based fine to very fine grained sandstone beds, which represent distal storm deposits. Some of these beds contain abundant *Skolithos*, which may represent recolonisation of the seafloor following disruption of the bottom community by storm activity. The small size, abundance, and localised occurrence of these *Skolithos* provides evidence for opportunistic recolonisation of the seafloor.

ACKNOWLEDGEMENTS

This project was offered to me by S. George Pemberton, who provided the impetus for some interesting research opportunities during my time at the University of Alberta. His supervisory role is gratefully acknowledged, as is his generous funding of thesis work.

Financial considerations were provided by Esso Resources Canada and NSERC operating grants to S.G. Pemberton. University of Alberta teaching assistanship, summer research fellowship, Canadian Society of Petroleum Geologists Petroleum Geology Scholarship, and many generous loans from Vern and Donna Vossler contributed to the financial security of the author.

Maps, photos, and core locations were provided by F.Krause, S. Leggitt, K. Bergman, Esso Resources, and H. Oppelt. Various tools were loaned to me by J. Magwood, M. Ranger, A. Fox, and B. Mattison.

Critical review of various parts of this thesis, especially the *Skolithos* paper (published in Lethaia), from S. Speyer was indispensible to the author and many thanks are extended for this and as well for much critical discussion on various thesis related ideas.

My fellow ichno-students James P.A. Magwood and B. W. Mattison reviewd almost all parts of this work, and continued to speak to me even after I beat them with their revisions.

Greg Edgecombe was a patient critic of my writings and ideas, as well he was a constant inspiration wiht his enthusiasm for paleontology and science in general.

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CHAPTER ONE: INTRODUCTION

In economic petroleum geology, the cutting of core to examine lithologies present in the subsurface has become a standard practise. These core hold a wealth of information, since they allow researchers to see strata which has not undergone the vagaries of weathering; this is especially beneficial in the study of muddy lithologies. In mudrocks, biogenic structures (or ichnofossils) can be especially significant, since frequently physical sedimentary structures are rare. It would seem, then, that the study of ichnofossils in core is essential to the understanding of shaly units in the subsurface.

One of the most important producing formations in Alberta is the Cardium Formation (Upper Cretaceous: Turonian) which consists predominantly of mudstones with less abundant sandstones and conglomerates. This formation occurs throughout western Alberta in outcrop and subsurface (Fig. 1). Outcrops of the Cardium Formation in the Foothills and mountain regions of western Alberta are distant from subsurface plays and may be stratigraphically unrelated to them (Walker, 1986). Thus, the study of core must play an important role in understanding the Cardium Formation. The objective of this thesis is to enhance understanding of the Cardium Formation in the Pembina area through a detailed examination of ichnofossils present in core from this oilfield, and nearby related oilfields.

The Cardium Formation is a member of the Upper Cretaceous Alberta Group and it is late Turonian in age (Stelck, 1955). It is comprised predominantly of sandy mudstones and mudstones with thin sands and conglomerates which distinguish it from the underlying Blackstone Formation (Stott, 1963). The sandiness of the Cardium Formation suggests that it represents a regressive phase, seperating two major transgressions in Turonian-Santonian time (Williams and Stelck, 1975). Late Turonian time was a period of extensive flooding during which the western interior of North

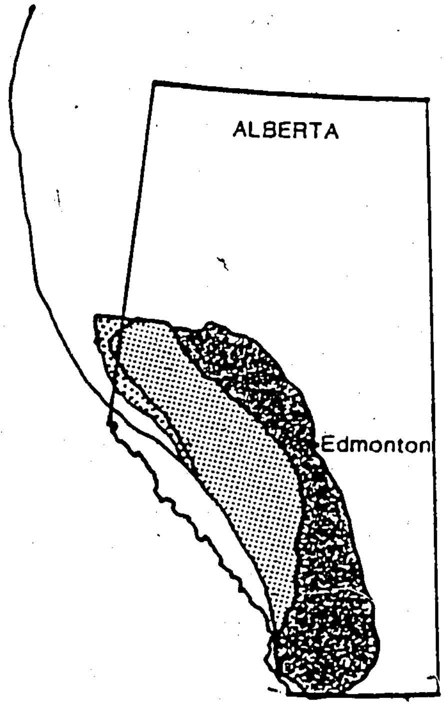

Figure 1. The extent of the Cardium Formation in outcrop and subsurface. Thick dots represent marginal marine deposits, small dots indicate nearshore marine sandstones and grey shading indicates marine mudstones. The line to the left indicates the edge of the deformed belt. (modified from Nielsen and Porter, 1984).

America was covered by an epeiric seaway (Barron, 1987, fig. 4; p.211).

The division of the Cardium Formation into members in outcrop was first tackled by Stott (1963). His member stratigraphy does not correspond to coarsening sequences which he also delineated. Duke (1985) revised the outcrop stratigraphy of the Cardium Formation so that members correspond to coarsening upward cycles, however this appears only in an unpublished Ph.D. thesis.

Subsurface stratigraphy is difficult to correlate to outcrop stratigraphy (Stott, 1963; Plint *et al.*, 1986). Due to the use of informal names and industry production zone names (which vary between oilfields), the subsurface stratigraphy of the Cardium Formation was in a state of turmoil, as reviewed by Krause and Nelson (1984). A revised stratigraphic nomenclature was proposed by these authors. A more extensive review of Cardium Formation subsurface stratigraphy was given by Plint *et al.* (1986; 1987) and another set of member names for the subsurface was proposed. This new nomenclature for the Cardium Formation is based upon 'event stratigraphy' principles, using coarsening upward sequences and pebble/conglomerate horizons as unconformity bounded members. Plint *et al.*'s stratigraphy is useful and appears sound in the study area. Thus, the member names as proposed by Plint *et al.* (1987) are used herein.

PREVIOUS WORK

The name Cardium was first applied by Hector (1858 in Whiteaves, 1895) to the shales outcropping at Old Bow Fort, on the Bow River in the Foothills of southern Alberta. The name Cardium Shale was used since abundant bivalves identified by Hector and Whiteaves (in Whiteaves, 1895) as members of an undetermined species of the genus *Cardium* were collected in the shale. Cairnes (1907) subdivided the Cardium shales into (in descending order): the Claggett Shale, the Cardium Sand, and the Benton

Shale.

The Alberta Group was delineated as being comprised of the Wapiabi Formation, the Cardium Formation and the Blackstone Formation by Webb and Hertlein(1934). In the central Foothills these authors found that the Cardium consists of a series of hard sandstone and sandy shale beds, with conglomerates and siderite nodules also present. *Cardium pauperculum (sic)* was commonly collected in these beds. These authors assigned an early Coniacian age to the Cardium Formation.

Modern research on the Cardium was sparked by major hydrocarbon discoveries in the formation in the early 1950's. Pembina exploration was initiated with the drilling of Socony Seaboard Pembina #1, which was completed on July first, 1953 (Irwin, 1954; Nielsen and Porter, 1984). Oil was found in the then unexplored Cardium sand. In 1954, Irwin noted that Pembina may be the largest conventional reservoir in Canada, which it has since proven to be.

Harding (1955) studied the Cardium in outcrop and found that the formation is present throughout the length of the Alberta Foothills. The age now accepted for the Cardium Formation was determined by Stelck (1955), from ammonite and bivalve zonations for the Upper Cretaceous, to be latest Turonian. The Cardium Formation was proposed as a northern equivalent to the Frontier Formation in the western United States on this basis (Stelck, 1955). The same author also recognised unconformities present in the Cardium Formation and related them to sea level fluctuations.

In a study of the Cardium Formation in subsurface, Floyd Beach opened Cardium controversy by proposing that the formation represented a series of turbidite deposits, a concept which was new in the geological community (Beach, 1955). In 1956, De Weil criticised this model as an example of band-wagon jumping, but Beach (1956) countered this attack. In the next year, the Alberta Society of Petroleum

Geologists held a symposium on the Cardium. Mountjoy (1957) proposed beach and detaic deposition as the source of the Cardium Formation sandstones and conglomerates. Nielsen noted the distribution of sandstone beds and concluded that the conglomerate was deposited on the "partially scoured and semiconsolidated surface of the upper sands". Michaelis (1957) concluded that tidal deposition in a shallow sea had formed the Cardium. As well, Roessingh (1957) and Patterson and Arneson (1957) noted the presence of a structural hinge line running through the Cardium oilfields discovered up to that time.

In 1969, Michaelis and Dixon published a very detailed examination of the Cardium Formation in the Pembina oilfield. From this study of the sedimentary characteristics of the Cardium, it was concluded that while wave and storm influence is present in the deposits, tidal currents were the main depositional agent.

The recognition of storm dominated deposition in the Cardium began when Swagor *et al.*(1976), concluded that storms had carried pebbles onto shelf deposits of the Cardium Formation in the Carrot Creek area. In a now classic paper, Wright and Walker (1981) described hummocky cross-stratification from excellent Cardium Formation exposures at Seebe dam, Alberta. In 1983, storm deposition was proposed as a depositional mode for various subsurface occurrences of the Cardium Formation (Walker, 1983a; b). Another flurry of Cardium papers appeared in 1984, in general confirming storm dominated deposition for the Cardium sandstones (Pemberton and Frey, 1984; Krause and Nelson, 1984; Nielsen and Porter, 1984). The MacMaster Cardium Research Group has been responsible for many of the recent Cardium works (Walker, 1985; 1986; Keith, 1985; Duke, 1985; Bergman and Walker, 1986; 1987, Plint *et al.*, 1986; 1987; Plint and Walker, 1987; Leggitt, 1987; Bartlett, 1987, and others). Opposing viewpoints to the MacMaster Group ideas (the most recent of which have centred on the importance of unconformity surfaces in the Cardium Formation) have been offered by Smith (1985), Hayes and Smith (1987) and Rine *et al.* (1987).

METHODS AND MATERIALS

The cored Cardium Formation interval was examined in 110 core from the Pembina-Carrot Creek oilfields area of west central Alberta. Core were studied at the Energy and Resources Conservation Board Core Research Centre in Calgary, Alberta. The core were depth corrected by correlating them to available wire-line logs (gamma ray, resistivity, spontaneous potential). Ichnofossils and lithologies were logged (refer to appendix B). Brief descriptions of ichnogenera present in the Cardium Formation are given in Appendix A.

Core were selected by: A) well locations provided by F. F. Krause, B) a random sampling of various areas of the Pembina oilfield, C) well locations in the Carrot Creek area suggested by K. Bergman and D) a detailed examination of available core from township 50-11 west of the 5th Meridian.

In addition, the base of conglomerate contact was examined in core from an additional 49 wells (refer to appendix C).

THESIS SUBDIVISION

In the course of early thesis work, three distinct subdivisions of the topic became clear: 1) description of common ichnogenera in the Cardium as they appear in core, 2) the overall ichnology of Cardium Formation sandstones and mudstones, 3) a firmground ichnofauna found at the base of the conglomerate and it's significance for sequence stratigraphy, and 4) opportunistic ecology as represented by *Skolithos* from the Cardium Formation. These four topics are the basis for four seperate research papers presented herein.

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CHAPTER TWO: ICHNOFOSSIL DESCRIPTIONS

The identification of ichnofossils in core is somewhat problematic and is dependent to a great extent on the ability of the observer to project the limited view offered by core into a three-dimensional plane. The examination of core is a primary tool in petroleum geology, and for many formations it is the only avenue for hands on observation of lithologies and biogenic structures present. Core allows examination of continous vertical section without the vagaries of weathering. In this way, core is superior to outcrop for the examination of bioturbated mustones which may be reduced to rubble in outcrop. This is obviously an advantage in the muddy parts of the Cardium Formation. The disadvantages of core are the poor lateral control to the wide spacing of wells, and the narrow (2-4") diameter view provided by core which obscures large scale structures.

The only comprehensive work on the identification of ichnofossils in core is Chamberlain (1978). Although this work is almost 10 years old, very little published work on identifying ichnofossils and interpreting them from core has been written since. With this in mind, it does not seem redundant to describe herein ichnogenera from the Cardium as they appear in core. Most ichnofossils from core can be identified only to the ichnogeneric level, since core sections do not offer sufficient information for ichnospecific distinction. Photographs (Plates 1,2, 3) and line drawings (Fig. 2) are given to illustrate the appearance of ichnogenera. Brief discussion of the signigicance of particular ichnogenera as they occur in the Cardium are also given. When ichnologists begin to use the vast information available from core, a greater knowledge of producing formations can be gained, to the benefit of both academic and economic pursuits in geology.

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1. A version of this chapter has been submitted for publication. Vossler, S.M. and Pemberton, S. G.,

1988. C.S.P.G. Core conference, 1988.

Arenicolites

Description: Simple U-tubes perpendicular to bedding without spreite (Häntzschel, 1975). In core, *Arenicolites* is easily mistaken for *Skolithos*. but it can be distinguished by a J or U shape. In the core examined, *Arenicolites* was unlined to very thinly lined, with average tube diameter of 0.3 cm. and average length of 3.6 cm.

Discussion: *Arenicolites* is very similar to the burrows of the modern lugworm *Arenicola*, for which it is named (Salter, 1857). The lugworm pumps water through the U-shaped burrow, bringing nutrients into one end of the tube and removing waste through the other end (Barnes, 1980).

Arenicolites has been reported from the upper shoreface (Howard and Frey, 1984), mixed tidal flats (Mattison, 1987), and the high energy intertidal, shallow subtidal zone (Fürsich, 1974a). In the Cardium Formation, *Arenicolites* is found in sandy mudstones associated with storm generated thin sandstones.

Asterosoma

Description: Relatively large fan to star-shaped burrows with bulbous, spreitenless, outward tapering rays extending from a central shaft (Saunders and Pemberton, 1986). In core, *Asterosoma* appears as oval burrows with concentric laminae of sand and clay sized material packed around a central tube. Average diameter of Cardium specimen is 1.5 cm., with the height approximately one half of the width. The burrows frequently occur in small clusters, suggesting many branched forms.

Discussion: *Asterosoma* may be either the dweling-grazing burrow of a decapod crustacean (Häntzschel, 1975) or the feeding trace of a vermiform organism repeatedly probing the sediment to enlarge the gallery and work more sediment vertically and

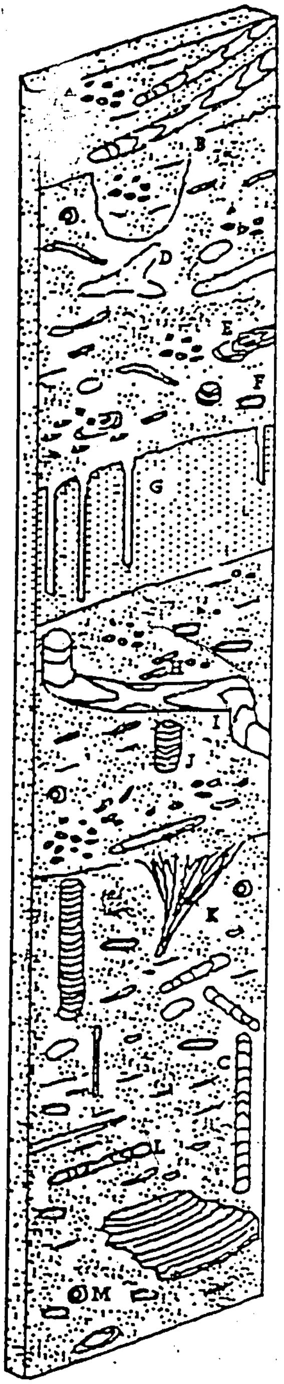

Figure 2. The appearance of common ichnogenera from the Cardium Formation in core. A. *Chondrites*; B. *Bergaueria*; C. *Diplocraterion*; D. *Thalassinoides*; E. *Asterosoma*; F. *Palaeophycus*; G. *Skolithos*; H. *Planolites*; I. *Zoophycos*; J. *Teichichnus*; K. *Rosselia*; L. *Rhizocorallium*; M. *Terebellina*. (modified from Chamberlain, 1978).

Plate 1. a. *Diplocraterion*. b. Small arrow indicates *Palaeophycus*; large arrow *Ophiomorpha*. *Planolites* also present; c. *Ophiomorpha*; d. *Zoophycos*. All scale bars 1 cm.

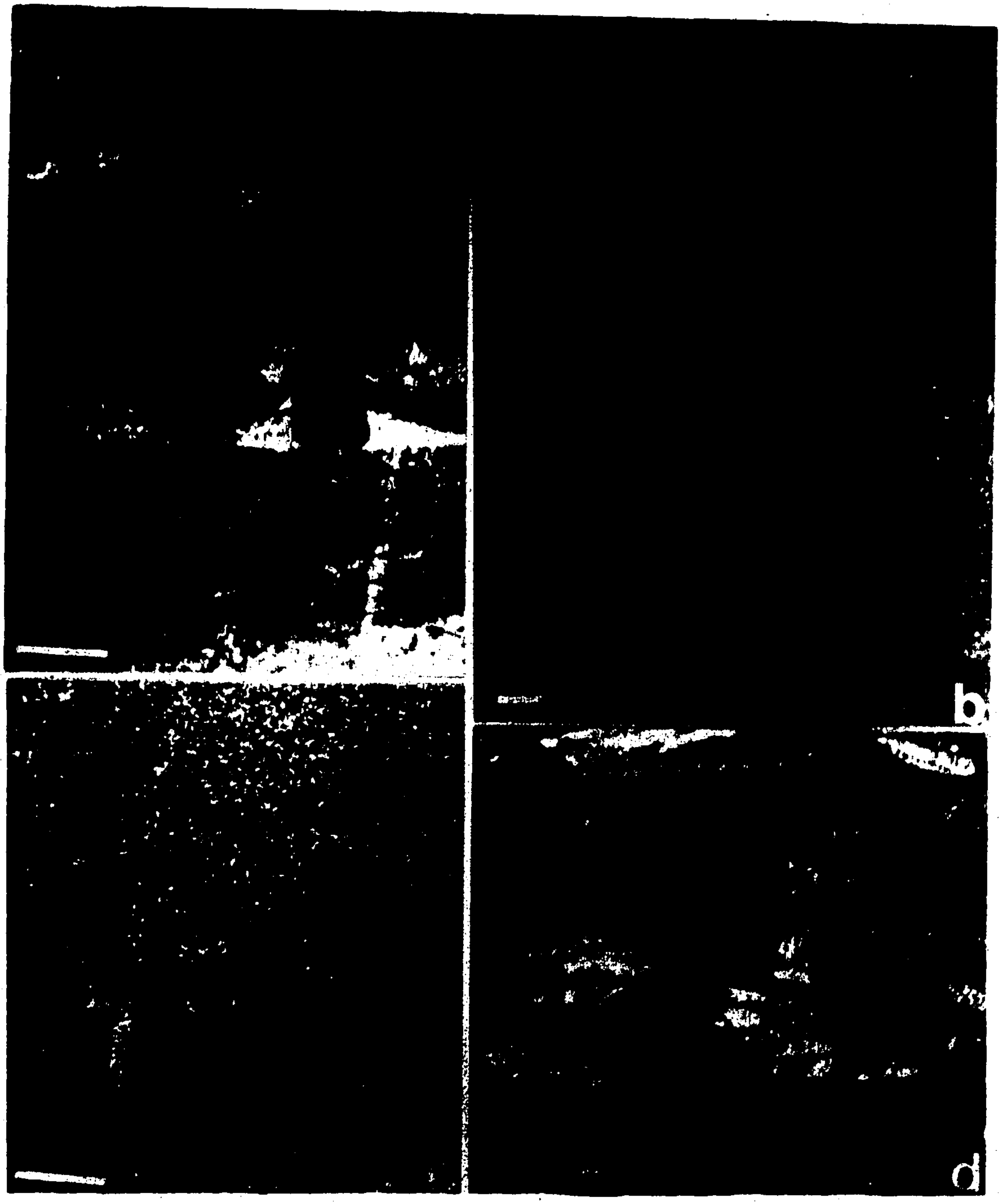
b
d

Plate 2. a Small arrows indicate *Chondrites*. Large arrow indicates *Planolites beverlyensis*; b. *Rosselia*; c. Long dark arrow points to *Asterosoma*, small dark arrow indicates *Planolites montanus*, open arrow indicates the base of *Rosselia*; d. Arrows point out the left edge of a large escape trace. All scale bars 1 cm.

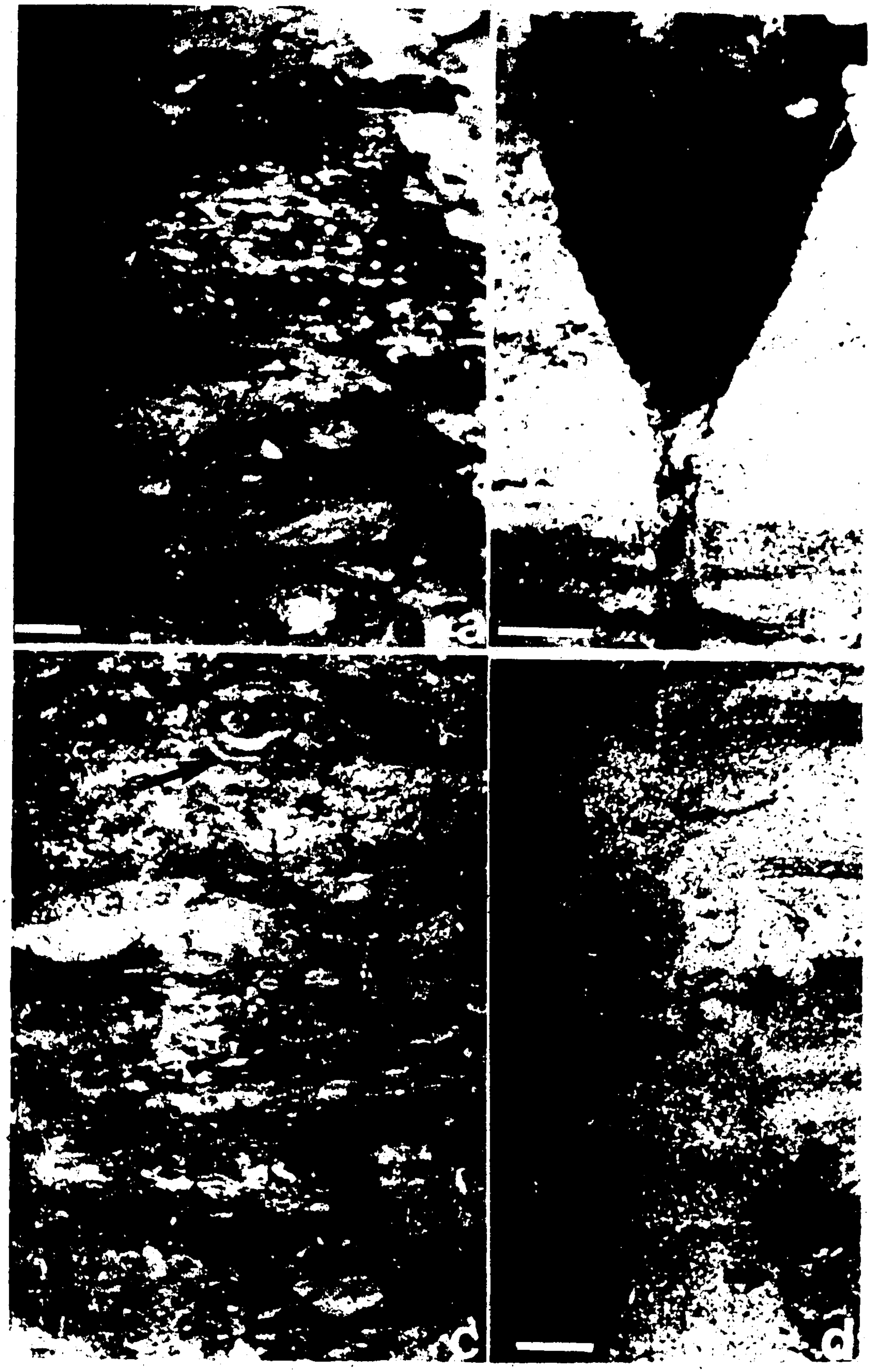
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Plate 3. a. Large dark arrow points to *Thalassinoides*. A well defined *Skolithos* occurs just to the left of this. The open arrow points to Asterosoma; b. A bedding plane view of *Lockeia* (top of photo) and *Didymaulichnus* (trail at bottom of photo), preserved at the top of a mudstone bed; c. *Helminthopsis*; d. *Teichichnus*; e. *Rhizocorallium*, arrow points to tube; f. *Cylindrichnus*. All scale bars 1 cm.


b
c
e
f

laterally (Chamberlain, 1971). Since it is formed in a similar manner, *Asterosoma* may be gradational with the vertical burrow *Rosselia*, which is formed in a similar manner.

Asterosoma has been reported in upper bathyal conditions along with *Neonereites, Nereites, Spirophyton,* and *Zoophycos* (Crimes, 1981); delta front-distal bar environments in addition to *Zoophycos, Terebellina, and Teichichnus* (Basan and Petersen, 1981), and shoreface environments (Frey & Howard, 1984) In the Cardium Formation it occurs in sandy mudstones , interbedded sandstones and mudstones and fine grained sandstones.

Bergaueria

Description: Cylindrical to hemispherical, vertical burrows possessing smooth unornamented walls, structureless infill, rounded bases, often with a shallow central depression and radial ridges (Pemberton *et al.*, in press). In core, *Bergaueria* can be recognised as broad pits, which are several centimetres deep, with roughly equal height and width.

Discussion: *Bergaueria* is not frequently found in the Cardium Formation. This ichnogenera is one of many plug-shaped burrows which can be attributed to anenomes (Pemberton *et al.*, in press). It is distinguished from *Conichnus* by it's broader, more bowl-like shape.

Chondrites

Description: Dendritic patterns of small cylindrical regularly branching tunnel systems, which do not normally interpenetrate or crossover (Hantzschel, 1975; Pemberton and Frey, 1984). In core, *Chondrites* is recognised as clusters of sharp walled, very small oval burrows, with fill contrasting with the matrix It is distinguished from *Planolites* *montanus* by its (1) narrow diameter, (2) oval cross section, (3) tendency to occur in (4) dense clusters, and (5) very sharp walls. The infill of *Chondrites* is frequently a bright white colour, which is easily discerned in muddy units.

Discussion: The sharp-walled nature of *Chondrites*, in addition to it's tendency to reburrow other traces, (especially *Thalassinoides*) indicates that it represents the activities of deep burrowing organisms. It has been postulated that *Chondrites* behavior may be tolerant to reduced oxygen in the sediment (Ekdale, 1985). Superabundance of *Chondrites* in some mudstone interbeds in the Cardium Formation may be a response to storm buried organic material (Vossler and Pemberton, 1988).

Chondrites is probably the feeding burrow of either a sipunculid or polychaete worm (Simpson, 1957; Schäfer, 1972). The organism may have extended a proboscis from a fixed base on the seafloor, to systematically probe the sediment (Simpson, 1957).

Conichnus

Description: Conical, amphora-like, subcylindrical, vertical burrows, generally with rounded bases (Pemberton *et al.*, in press). In core, *Conichnus* has almost a v-shaped profile, with height greater than width, heights frequently being more than 10 cm.

Discussion: *Conichnus* is rare in the Cardium, and is generally found in sandstones. Conichnus has been interpreted as a dwelling burrow of anenome or anenome-like organism. It is distinguished from *Bergaueria* by having a more cone-like morphology.

Cylindrichnus

Description: Subcylindrical to subconical burrows, straight to gently curved, having multiple, concentrically layered walls, with a vertical to subhorizontal orientation with rare branching (Pemberton and Frey, 1984). In core *Cylindrichnus* appears as a wide, sand-filled shaft with multiple clay-linings and frequently a mud-filled core. The burrows are generally gently curved, with the diameter increasing upward. The average diameter is 2.1 cm. with heights generally 6-7 cm.

Discussion: It has been postulated that *Cylindrichnus* represents the dwelling or dwelling -feeding structure of vermiform animals (Howard and Frey, 1984). It is similar in apearance to burrows of the polychaete *Nereis* (see Reineck and Singh, 1980: p. 244). Other interpretations suggested that *Cylindrichnus* is the burrow of anenomes, or the siphonal shaft of burrowing bivalves, but the narrowness of the central shaft makes these interpretations unlikely (Chamberlain and Clark, 1973; Pemberton and Frey, 1984).

While *Cylindrichnus* is morphologically similar to *Rosselia*, *Cylindrichnus* is a lined dwelling burrow while *Rosselia* is a bulbous feeding trace. In core, *Cylindrichnus* is distinguished from *Rosselia* by its less bulbous form and by having overall more sand incorporated into the burrow.

Didymaulichnus

Description: simple, smooth, gently curving bilobate trails preserved in convex hyporelief, lobes seperated by a distinct furrow (Häntzschel, 1975). In core, *Didymaulichnus* is seen on bedding plane views of thin shale partings and as small indentions at the base of sandstone beds.

Discussion: *Didymaulichnus* from the Cardium Formation are likely surface trails preserved by storm events that blanket them with sediment. *Didymaulichnus* is frequenly found in close association with *Lockeia*. *Didymaulichnus* has been interpreted as a mollusc crawling trail. The occurrence of *Didymaulichnus* in the core of this study is the youngest known occurrence of this trace (Vossler *et al.*, in review).

Diplocraterion

Description: U-shaped burrow with spreite, vertical to bedding, limbs parallel or divergent. spreite are protrusive, retrusive or a combination (Pemberton and Frey, 1984). *Diplocraterion* is identified in core as a spriete-filled burrow which in some cases curves into a U or J-shape. The burrow tube may be exposed at one end. Both protrusive and retrusive burrows were observed.

Discussion: *Diplocraterion* was very rare in the core examined, and was found only in sandy mudstones. Tubes are less than 1 cm. in diameter and length is 10 - 15 cm.

Diplocraterion is the dwelling burrow of a suspension-feeding organism in an environment with unstable sedimentation rates (Fürsich, 1974b, Pemberton and Frey, 1984, Häntzschel, 1975). Possible trace-makers include polychaetes, echuiroids, and crustaceans.

Helminthopsis

Description: Simple meandering smooth trails, but not as strictly developed as *Helminthoida* (Häntzschel, 1975). *Helminthopsis* is recognised in core as a series of black dots, somewhat irregularly spaced, but which appear to occur on one bedding plane. Samples from the Cardium Formation in core have a 0.17 cm average diameter.

Discussion: *Helminthopsis* was initially seperated into ichnospecies on the basis of burrow diameter (Ksiazkiewicz, 1977). While this method has been criticised by some authors (Pickerill, 1981), no more satisfactory division has been proposed. Based on this, samples from the Cardium can be assigned to *Helminthopsis tenuis* Ksiazkiewicz, 1968 (in Ksazkiewicz, 1977). In core, distiguishing *Helminthopsis* from *Gordia* (similar to *Helminthopsis* but crosses over itself) is almost impossible (Pickerill, 1981).

It is distinguished from *Helminthoida* in core by the less regular pattern of burrow cross-sections.

In the Cardium Formation, *Helminthopsis* is found in mudstones, sandy mudstones and interbedded sandstones and mudstones. *Helminthopsis* is a facies breaking trace but is most frequently found in deeper marine settings (Pickerill, 1981). It is the grazing trail of a vermiform organism, most likely a polychaete (Häntschel, 1975). While *Helminthopsis* is generally regarded as a surface trace, its occurrence reburrowing other forms in the Cardium suggests emplacement at least slightly below the sediment/water interface.

Lockeia

Description: Small, almond-shaped, almost symmetrical oblong bodies preserved in convex hyporelief (Osgood, 1970). In the Cardium core, *Lockeia* is found on bedding planes of interbedded sandstones and mudstones, occurring as almond-shaped depressions which are 2-4 cm. long.

Discussion: As noted previously, *Didymaulichnus* and *Lockeia* are frequently found in close association. *Lockeia* has been interpreted as the resting trace of bivalves burrowing at the sediment-water interface (Osgood, 1970; Häntzschel, 1975).

While some authors use the name *Pelecypodichnus* rather than *Lockeia* (eg. Eagar *et al*, 1985), the latter term has precedence and should be retained (Häntzschel, 1975).

Ophiomorpha

Description: Simple to complex burrow systems with a distinct lining of agglutinated pelletoidal sediment (Frey *et al*., 1978). In core, *Ophiomorpha* occurs as variably oriented, cylindrical burrows with a thick knobby lining. Cross sections are generally oval to circular.

Discussion: Based on close modern analogs, *Ophiomorpha* has been interpreted as the dwelling/feeding structure of shrimp or shrimp-like animals. The ichnogenus *Thalassinoides* is similar to *Ophiomorpha* in general morphology but lacks a knobby wall lining. In the Cardium Formation, *Ophiomorpha* is associated predominantly with sandy units.

Palaeophycus

Description: Branched or unbranched, smooth or ornamented, lined essentially cylindrical, predominantly horizontal burrows of variable diameter, fillings typically structureless and of the same lithology as the host-rock (Pemberton and Frey, 1982). *Palaeophycus* appears as mud lined ovals or cylinders in core cross-sections, the fill is of the same lithology (and thus colour) as the encasing sediment.

Discussion: *Palaeophycus* has been interpeted as the dwelling structure of a suspension feeder or a carnivorous vermiform organism (Pemberton and Frey, 1982). The modern polychaetes *Glycera, Nereis succinea* and *Nereis virens* construct similar burrows (Pemberton and Frey, 1984). *Palaeophycus* is divided into ichnospecies on the basis of wall thickness and sculptings, but only thickness of the lining can be seen in core. On this basis, specimens from the Cardium sandstones and mudstones were assigned to the ichnospecies *Palaeophycus tubularis* and *Palaeophycus heberti*.

Palaeophycus tubularis

Description: smooth, unornamented burrows of variable diameter, thinly but distinctly lined (Pemberton and Frey, 1982). Average diameters of 0.68 cm. were found, with wall lining thickness of 0.03 cm.

Palaeophycus heberti

Description: smooth unornamented, thickly lined cylindrical burrows Pemberton and Frey, 1982). The averaage diameter of *P. heberti* was 0.5 cm. with wall thickness of 0.1mm. Core diameters for *P. tubularis* and *P. heberti* were very similar.

Planolites

Description: Unlined, rarely branched, straight to tortuous, smooth to irregularly walled or annulated burrows, circular to elliptical in cross-section, of variable dimensions, with a structureless fill differing in lithology from the host rock (Pemberton and Frey, 1982). In core, *Planolites* appears as ovals of contrasting sediment, usually lighter coloured than the host.

Discussion: Perhaps the most important distinguishing characteristic of *Planolites* is having the burrow fill differ in texture from the host rock, indicating that it has been processed by a deposit-feeding organism (Pemberton and Frey, 1984). Two ichnospecies of *Planolites* can be found in the Cardium, differentiated on the basis of burrow diameter: *Planolites montanus* and *Planolites beverlyensis*. *Planolites* is a facies breaking ichnofossil that occurs in mudstones, sandy mudstones, interbedded sandstones and mudstones and sandstones of the Cardium Formation.

Planolites montanus

Description: The mean diameter of samples measured was 0.25 cm. Burrow walls were generally somewhat 'fuzzy' indicating that the substrate was quite soft at the time of emplacement.

Planolites beverlyensis

Description: Oval to circular burrows of average diameter 0.7 cm., with light coloured infill. As in *P. montanus*, burrow walls were sometimes indistinct.

Rhizocorallium

Description: U-shaped spreiten burrows, parallel or oblique to bedding planes, limbs more or less parallel and distinct (Häntzschel, 1975). *Rhizocorallium* appears in core as a horizontal spriete-filled ribbon, with the tube present at one end. Rarely, both tubes are visible.

Discussion: In sandy substrates or at omission surfaces, *Rhizocorallium* may represent the dwelling burrow of a suspension-feeding organism. In muddy substrates, it is more likely the feeding burrow of a deposit-feeding organism. The presence of the tubes distinguishes *Rhizocorallium* from *Zoophycos* in core.

Rosselia

Description: Conical to irregularly bulbous or funnel shaped structures, vertical to subvertical, consisting either of a small central tube surrounded by broad, concentric, cone-in-cone laminae or of spreite-like helicoidal swirls surrounding a core, tapering down to a narrow concentrically lined stem (Pemberton and Frey, 1984). *Rosselia* is recognised in cross-section by a mud-lined funnel tapering downward. Only rarely is the sandy central shaft visible. Average bulb diameter was 2.5 cm.

Discussion: *Rosselia* is interpreted as the burrow of a deposit-feeding organism working outward from a central point (Chamberlain, 1971). It is distinguished from

Cylindrichnus by a more bulbous shape and overall muddy character.

Skolithos

Description: Straight tubes or pipes perpendicular to bedding, cylindrical to subcylindrical, unbranched, straight. In core, *Skolithos* appears as a vertical shaft. Dimensions were extremely variable, with diameter ranging from a few mm to almost a cm, and lengths from one cm to over 10 cm.

Discussion: Despite the relatively simple and easily recognised morphology of *Skolithos*, it is in a state of taxonomic chaos (Mattison, 1987).

Skolithos is the domicile of suspension-feeding vermiform organisms, most likely polychaetes or phoronids (Pemberton and Frey, 1984). In the Cardium Formation, *Skolithos* is most abundantly found in thin storm sandstones, indicating opportunistic recolonisation of the seafloor (Vossler and Pemberton, in press).

Thalassinoides

Description: Cylindrical burrows forming three-dimensional branching systems consisting of horizontal networks connected to the surface by vertical shafts. Regularly branching Y- or T-shaped bifurcations forming polygons with swelling typical at junctions (Häntzschel, 1975). Recognised in core as oval to circular burrows greater than 1 cm in diameter, with infill contrasting with surrounding sediment.

Discussion: *Thalassinoides* is most likely the burrow of a crustacean such as a thalassinid shrimp. It is distinguished from *Ophiomorpha* by the absence of a lining. *Thalassinoides* is abundant in bioturbated mudstones of the Cardium Formation.

Teichichnus

Description: Spreiten structures consisting of several closely concentric horizontal or inclined, longitudinally nested burrows, commonly retrusive but can be protrusive. In core, *Teichichnus* is seen as spriete-filled ovals, or long, tapering structures with a longitudinal view of the spreite.

Discussion: *Teichichnus* is formed by a horizontally-burrowing deposit-feeding organism excavating the substrate from a more or less fixed position (Pemberton and Frey, 1984). In the core examined, *Teichichnus* was confined to muddy lithologies.

Zoophycos

Description: Complex spreiten structures with numerous morphologic variations, comprising two basic forms: helicoidal or flat-planar (Häntzschel, 1975). In core sections, *Zoophycos* appears as horizontal to subhorizontal ribbons with an average diameter of 0.8 cm, characterized by alternating light and dark spreite.

Discussion: *Zoophycos* is common in the Cardium in mudstones and sandy mudstones. It tends to cut other burrows, suggesting it represents a late stage of deep burrowing. *Zoophycos* is most likely the grazing burrow of a deposit-feeding vermiform organism (Wetzel and Werner, 1981). *Zoophycos* has been found in all water depths, although it is generally associated with quiet water conditions (Chamberlain, 1971; Marintsch and Finks, 1978). In Mesozoic strata *Zoophycos* is almost exclusively restricted to shelfal environments (Bottjer *et al.*, 1987).

Fugichnia (escape traces)

Description: perturbations in sedimentary fabrics, ranging from well formed and funnel-shaped to simple breaks in laminae. Size ranges from 10's of cm to 1-2 cm.

Discussion: Schäfer (1972) defined escape traces as "any escape effort triggered by an external adverse cause", with changes in sedimentation rate being the most frequent cause. While escape traces can be formed in response to scour (eg. Sellwood, 1970), they are most frequently associated with rapid sedimentation events (Reineck and Singh, 1980; McCarthy, 1979, Fürsich, 1974b). Organisms are removed from oxygen-rich waters by rapid burial and will suffocate if they are unable to burrow out (Schäfer, 1972).

Fugichnia are abundant in the Cardium Formation sandstones, which is consistent with what would be expected in a storm-dominated setting.

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CHAPTER THREE: ICHNOLOGY AND PALAEOECOLOGY OF OFFSHORE SILICICLASTIC DEPOSITS (CARDIUM FORMATION).

INTRODUCTION

Storm dominated offshore (shelfal) depositional environments have become increasingly important in the search for hydrocarbon traps. With this increase has come the desire to understand the physical and biogenic structures associated with these deposits. While much sedimentological work has been done on Mesozoic clastic deposits, much less time has been spent on the palaeoecology of these rocks. Palaeocological information on siliciclastic shelf environments, especially those from the Mesozoic, is rather sparse. This is in part due to the scarcity of body fossils in these deposits. Only a few ichnological papers have specifically dealt with storm-dominated offshore clastics. Since shelfal sediments are characteristically totally homogenised by benthic organisms, knowledge of the ichnology is a key to any palaeoenvironmental study.

The Cardium Formation (Upper Cretaceous: Turonian) is the middle member of the Alberta Group. It is late Turonian in age and is roughly correlative to the Frontier Formation in the western United States (Stelck, 1955). It is the most important hydrocarbon producing formation in Canada's largest conventional oilfield, Pembina (Nielsen and Porter, 1984). Member stratigraphy for outcrop occurrences of the Cardium Formation was proposed by Stott (1963). Stott also recognised and named a series of coarsening upward cycles whose boundaries are not concordant with the members. Duke (1985) suggested a new member nomenclature for the Cardium based on these coarsening upward sequences, however his work found only in an unpublished

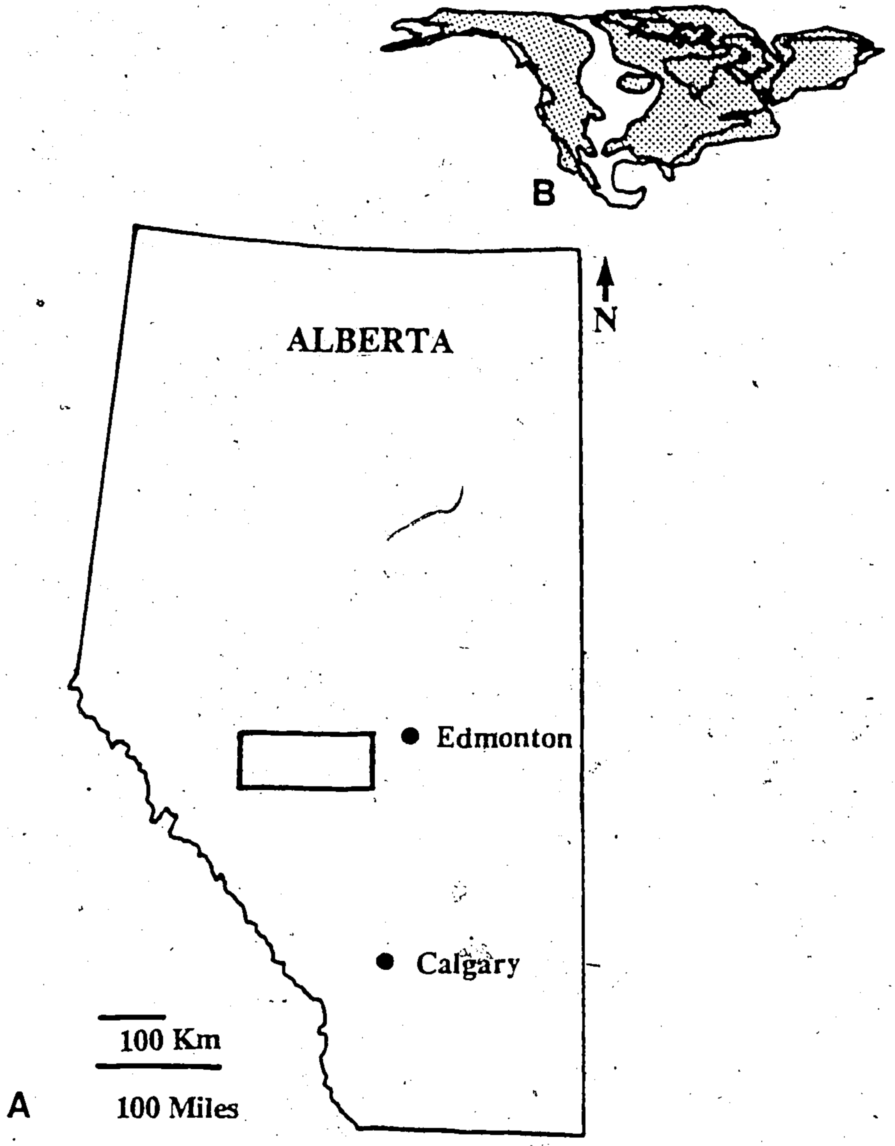

Figure 3. A. Study area within the province of Alberta, Canada. B. The Western Interior Seaway of North America in late Turonian time. (modified from Barron, 1987).

PhD. thesis and thus is not formally recognised (North American Commission on Stratigraphic Nomenclature, 1983). However, this has not prevented Plint *et al.*(1986) from promoting this scheme.

The members of Stott (1963) and of Duke (1985) have never been conclusively correlated with subsurface occurrences of the Cardium Formation. A series of informal 'industry names' for the sandstones have been used (eg. "Cardium A Sand") (Krause and Nelson, 1984). Krause and Nelson (1984) were the first to propose formal subsurface members for the Cardium based on their work in the Pembina oilfield. Plint *et al.* (1986, 1987) proposed another set of stratigraphic names for the Cardium Formation based on work from several subsurface occurrences of the Cardium, and working from an extensive data base of well logs and core. This nomenclature is based on the presence throughout the Cardium of coarsening upward sequences which are unconformably overlain by conglomerates or pebble veneers. Each genetically related package of sediment is given member status. Thus, in the Cardium Formation at Pembina, the lower sandstones and mudstones constitute the Raven River Member and the overlying conglomerates and marine mudstones constitute the Carrot Creek Member (Plint *et al.*. 1986, 1987). The top of the formation is marked by the 'Cardium Zone', a sideritised pebble band which is an easily recognised well log marker (Krause and Nelson, 1984). While the stratigraphic scheme of Plint *et al.* (1986, 1987) can be criticized for engendering genetic interpretation in its definition, the members as defined are physical realities which are useful since they depend on widespread, easily recognisable horizons. On this premise, the stratigraphy of Plint *et al.*(1987) is used in this study.

In this paper, the ichnology of the Raven River Member will be discussed. The

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1. A version of this chapter has been submitted for publication. Vossler, S. M. and Pemberton, S. G., in review. Palaeoclimatology, Palaeogeography, Palaeoecology.

ichnology of the Carrot Creek Member and the unconformity at the top of the Raven River Member are discussed in chapter 4. Examination of 110 core from the Cardium Formation in the Pembina oilfield (Fig. 3A) of west-central Alberta has provided the data to build a palaeoecological model for storm-dominated shelfal deposits.

The Cardium Formation is one of many Cretaceous formations in which storm dominated shelfal deposition has been interpreted as important (eg. the Viking Formation of Alberta; the Frontier Formation in Wyoming; the Shannon Formation in Wyoming, etc.). It occurs in outcrop in the Rocky Mountains and Foothills of Alberta and in subsurface throughout western Alberta. The eastern depositional edge of the formation is defined by shale-out into the Lea Park Formation. In subsurface and outcrop various authors have interpreted the Cardium Formation as storm-dominated (Michaelis and Dixon, 1969; Wright and Walker, 1981; Walker, 1983; Krause and Nelson, 1984; Pemberton and Frey, 1984; Duke, 1985; Bergman and Walker, 1986; Leggitt, 1987). Subsurface stratigraphy of the Cardium indicates that it consists of a series of thin sandstone and mudstone units seperated by conglomerates or pebble veneers (Plint *et al*, 1986). These sandstones are offshore deposits for which no correlative marginal marine deposits have yet been identified.

The Cardium Formation was deposited in an epeiric seaway which covered the western interior of North America during the Upper Cretaceous (Williams and Stelck, 1975; Barron, 1987) (Fig 3B). Most authors agree that this seaway was relatively shallow, with maximum depths proposed ranging from 30 to 1000 m (Parrish *et al.*, 1984). In Canada this seaway was bounded by the rising Cordillera to the west and the stable craton to the east (Kauffman, 1984). The Pembina oilfield may have been as far as 100 km from the shoreline at the time of deposition (Krause and Nelson, 1984). When sea level was low, the basin had restricted circulation with the ocean basins to the north and south and was probably at least moderately brackish; circulation was less restric during periods of high sea level and more normal salinities occurred (Kauffman, 1984). Terrane accretion (collision) was occurring to the west of the Cordillera throughout the Upper Cretaceous. Thrust faulting in the Rocky Mountains allowed downwarping and formation of a foreland basin in Alberta. On a large scale, three unconformity-bounded cyclothems are associated with three phases of Cretaceous tectonism. The Cardium Formation was deposited during the third phase -- from Cenomanian to Maastrichtian (and including the Tertiary) (Stott, 1987). Smaller cycles within this larger phase record pulses of tectonism. In this basin, sealevel changes were controlled by a complex interplay of thrust faulting, tectonic subsidence, sedimentation, climatic forces and eustatic sea level changes (Bilodeau, 1987). The cyclic nature of the Cardium Formation appears to be tied to these parameters as well.

The sedimentology and stratigraphy of the Cardium Formation has been extensively examined in outcrop and subsurface. Several of the most current of these studies have also dealt briefly with the ichnology of the formation (Krause and Nelson, 1984; Duke, 1985; Keith, 1985; Bergman, 1986; Leggitt, 1987; Bartlett, 1987), with only one study, Pemberton and Frey (1984), dealing primarily with ichnology. Among the sedimentological papers, the tendency has been to name only a few forms and to assign the ichnofossil assemblage to the ichnofacies concept as presented by Frey and Pemberton (1984). Unfortunately, a stringent use of the ichnofacies concept with respect to bathymetry only tends to simplify complex faunal/sediment relationships, leading to information loss and misinterpretation. Seilacher (1967) found that in simple situations, trace fosssil assemblages varied directly with depth. The complex setting of a storm dominated shelf may not be the best place for application of such a model.

Prior to a discussion of specific ichnological interpretations, a definition of important terms seems essential. An ichnocoenose is the natural association of lebenspurren reflecting benthic activities of respective members of the biocoenose, as opposed to an ichnofauna which is a group of ichnofossils which may not have direct relationships (Frey and Pemberton, 1985). In this study the ichnofossils of various temporally separated (but recurring) ichnocoenoses will be examined, as well as the more loosely grouped ichnofossil associations of which they are a subset.

SEDIMENTOLOGY OF STORM-DOMINATED OFFSHORE DEPOSITS

The sedimentology of storm deposits and storm-dominated shelfal deposits in the rock record has been examined by a plethora of authors. Some recently published examples for comparison with the Cardium are given here.

Brackett and Bush (1986) studied storm-dominated sedimentation on the muddy northern shelf of Puerto Rico. Two major rivers deposit terrigenous sediment onto the shelf. Episodic river flooding forms "inundites" (mud blankets) while oceanic storms lead to the deposition of "tempestites" (sand blankets). The slope of the shelf off Puerto Rico is relatively steep in contrast to the gently sloping shelf associated of the Western Interior Seaway. One individual storm deposit (a tempestite overlain by an inundite) was located in 32 drill cores taken from the shelf. This storm deposit ranged in thickness from 50 cm proximally to 1 cm in distal areas. The storm bed was normally graded. Escape structures were infrequently present. The dominant physical feature (observable in core) was plane parallel lamination. Such a storm bed may be analogous to isolated thin sandstones or an individual bed in an amalgamated sequence in ancient shelfal sequences.

Tye *et al.* (1986) examined the sedimentology of the Upper Cretaceous Shannon Sandstone Member of the Pierre Shale. The Shannon occurs as multiple sand ridges on the submarine shelf in the North American Interior Seaway (Upper Cretaceous). A coarsening sequence is present, comprised of shale, bioturbated siltstone, burrowed shaley fine sandstone, laminated and rippled shaley sandstone, cross-bedded to rippled coarse to medium grained sandstone, and cross-bedded to fine sandstone.

In some places within the Denver Basin, the Terry Sandstone Member of the Pierre Shale displays a coarsening upward sequence of bioturbated sandy mudstone and sandstone, rippled to burrowed sandstone, rippled to burrowed sandstone and rippled to cross-bedded sandstone (Siemers and Ristow, 1986). In both of the above examples, the sandstones are encased in marine shales. Widespread (rather than ridge-like) shelfal sandstone deposits were described by Thompson *et al.*(1986) from the Upper Cretaceous Ferron Sandstone Member of the Mancos Shale. The widespread coarsening upward sequences are attributed to "delta plume" deposition and subsequent reworking by storm waves and benthic organisms.

The specific sedimentology of shelf construction in a foreland basin has been documented by Swift *et al.* (1987) for the Upper Cretaceous Mesaverde Group in Utah. The Mesaverde Group is a shelf sequence which prograded into a subsiding basin. Laminated shale, interbedded sandstone and shale and amalgamated sandstones comprise a coarsening upward sequence which is interpreted as a shelf to middle shoreface progression. Local lag sandstones and channel fill shale represent submarine erosion at the shelf edge.

Outside of the Cretaceous Interior Seaway, widespread storm dominated shelfal sandstones have been reported from the Miri Formation (Miocene) of Brunei (Atkinson *et al*, 1986). Minor regressive-transgressive cycles are reported from an overall regressive sequence. Shale, bioturbated sandstone and shale, and laminated sandstone and shale with rare trough cross-beds comprise the coarsening upward sequences. The general trend is one of coarsening with decreased bioturbation, reduced faunal diversity and increased sandstone amalgamation upward. Shelf regression and shoaling was followed by transgession and deepening in this example.

A hummocky cross-stratified shelf-shoreface sequence was examined by Brenchley *et al.* (1986) from the Middle Ordovician Monte da Sombadeira Formation in Iberia. A facies sequence of mudstone and fissile siltstone, laminated siltstone and mudstone, thin bedded hummocky-cross stratification and amalgamated hummocky cross-stratification represents a muddy shelf -sand to shelf-shoreface transition.

ICHNOLOGY OF ANCIENT OFFSHORE DEPOSITS

Very few ichnological studies have been undertaken specifically to examine shelf clastic deposits, although many have dealt with them peripherally. Some sedimentological papers name a few cosmopolitan and easily recognisable forms (eg. *Ophiomorpha*, *Teichichnus*, *Zoophycos*, etc.) but few interpretations have been drawn from these ichnofossils, with more stress placed instead on the overall degree of bioturbation (Tye *et al.*, 1986; Atkinson *et al.*, 1986; Siemers and Ristow, 1986 etc).

From ichnological works which deal with storm influenced offshore/shelfal deposits some generalisations can be drawn. Detailed tabulation of ichnogenera associated with shelf deposits is given in Table 1. Deposit-feeding seems to be the dominant feeding strategy represented in the ichnology of fairweather deposits (Howard and Frey, 1984; Pemberton and Frey, 1984; Frey and Howard, 1985; Clausen and Vilhjalmssen, Hurst and Pickerill,1986; Bjerstedt, 1987). More specifically, offshore/shelfal deposits are associated with deep deposit feeding traces such as *Zoophycos* and *Chondrites* in addition to shallower forms such as *Planolites* and *Thalassinoides* (Pemberton and Frey, 1984; Howard and Frey, 1984; Frey and Howard,

TABLE 1: SHELFAL ICHNOLOGY

Author and Formation	Lithology	Ichnogenera
Frey and Howard, 1984 Star Point and Blackhawk Fm., U. Cret.	impure, mottled siltstones	*Scolicia, Palaeophycus, Cylindrichnus, Ophiomorpha, Teichichnus, Planolites Anchorichnus, Thalassinoides.*
Frey and Howard, 1985 Star Pt. Fm, U. Cret.	bioturbated siltstone	*Ophiomorpha, Palaeophycus,Uchirites, Ancorichnus, Rosselia, Thalassionoides, Chondrites, Schaubcylindrichnus, Planolites, Muensteria*
Claussen and Vilhjalmsson, 1986 Laesa Fm. L. Cambrian	siltstone, thin sandstones	*Diplocraterion, Buthotrephis, Planolites, Palaeophycus, Skolithos, Teichichnus, Rhizocorallium*
Hurst and Pickerill, 1986 Ross Brook Fm. Silurian	silty mudstones bioturbated to mottled	*Chondrites, Planolites, Helminthopsis, Palaeophycus*

Table 4 continued

Author and Formation	Lithology	Ichnogenera
Mattison, 1987 Clearwater Fm. L. Cret.	glauconitic muddy sandstones	*Skolithos*, *Planolites*, *Zoophycos*, *Chondrites*, *Rhizocorallium*, *Asterosoma*, *Conichnus*, *Diplocraterion*, *Palaeophycus*
Bjerstedt, 1987	mudstones and fine-grained sandstones	*Arthrophycus*, *Bifungites*, *Cruziana*, *Chondrites*, *Planolites*, *Palaeophycus*, *Rosselia*, *Rusophycus*, *Skolithos*

Plate 4. A. Homogenised mudstone (F2); B. homogenised sandy mudstone (F3); C. homogenised muddy sandstone (F4), note the possible *Spirophyton* burrow in the centre of the photo; D. highly bioturbated interbeds (F5). All scale bars are 1cm.

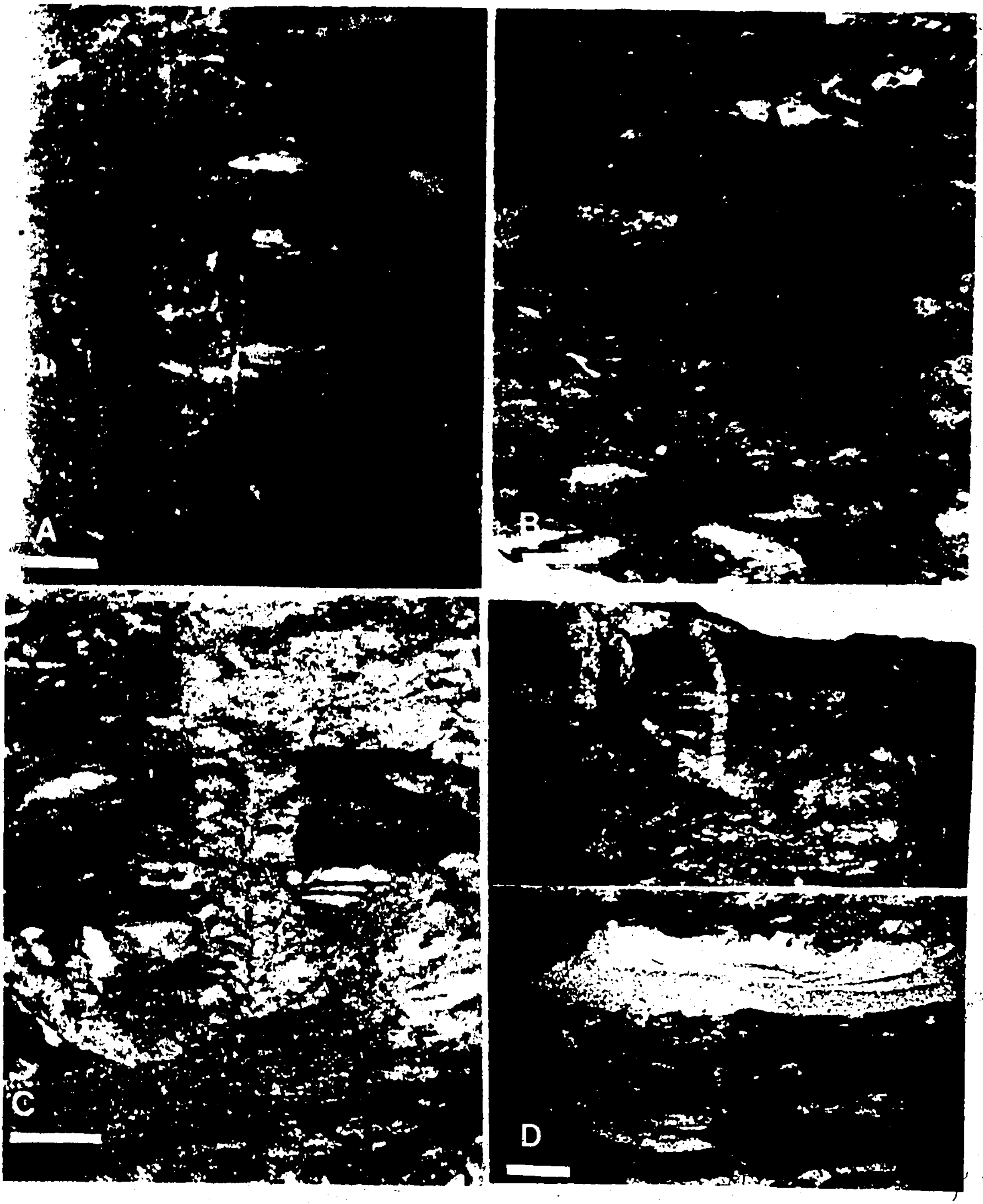
A
B
C
D

Plate 5. A. Interbedded sandstone and mudstone with only mudstones bioturbated; B. bioturbated sandstones (F7); C. unbioturbated sandstone (F8); (note well developed wave-ripples); D. planar-bedded to gently undulating sandstone (F8). This is possibly interpreted as hummocky-cross stratification. All scale bars are 1cm.


A
B
C
D

1985; Mattison, 1987). In many offshore settings, bioturbation is so pervasive that initially interbedded sediments are completly homogenised by biogenic reworking (Pemberton and Frey, 1984; Howard and Frey, 1984; Frey and Howard, 1985; Hurst and Pickerill, 1986, Bjerstedt, 1987). Only thick storm-generated sandstones can be preserved with little or no bioturbation (Howard and Frey, 1984; Frey and Howard 1985; Hurst and Pickerill, 1986; Vossler and Pemberton, in press). An interesting observation in storm deposits is the presence of two distinct groups of ichnofossils. One group is comprised of predominantly suspension-feeding behaviors, and another consists predominantly of deposit-feeding behaviors (Pemberton and Frey, 1984; Claussen and Viljalmsson, 1986; other examples as tabulated in chapter 5, Table 5. It has been proposed that the suspension-feeding ichnofossils represent the activities of opportunistic organisms recolonising the substrates following storm disruption (Pemberton and Frey, 1984; Vossler and Pemberton, in press). Opportunistic behavior in the ichnofossil record is characterised by abundant, simple suspension-feeding burrows, which may be relatively small. The occurrence of opportunistic behavior as represented by *Skolithos* in the Cardium Formation is discussed in greater detail in chapter 5.

MODERN SHELF DEPOSITS: FAUNAL ASPECTS

On modern shelves bioturbation is a very significant modifier of sedimentary structures. Relatively thick (20 cm) storm-generated sand blankets observed by Hayes (1967) were completely unrecognisable less than 20 years later due to mixing by bioturbation (Dott, 1983). In a study of core form the East China Sea, a variation in sedimentary structure preservation based on the degree of bioturbation was noted by Rhoads *et al.* (1985). While the shelf in this area is more tidal than storm-dominated, some generalisations may have application in a study of the Cardium. Areas with very high sedimentation rates were found to have no benthic organisms, while areas with low sedimentation rates had a fauna comprised of generally deep burrowing organisms. Short term deposition rates were found to be more significant than net accumulation in excluding organisms. Extreme rates of physical disturbance limited infaunal activities to shallow tube dwelling. However, burrows of this type of bioturbation are easily obliterated by subsequent turbulence (Rhoads *et al.* 1985).

Gaston (1987) studied benthic polychaete distribution on the middle Atlantic Bight, a storm-dominated shelfal environment, and examined feeding habitats and motility. Interstitial carnivors were found in coarser sediments, possibly because of the greater available living space. Surface deposit-feeding, in general, decreased with depth, but increased at the shelf break. This feeding mode was negatively correlated with fine grained sediment and with organic carbon. On the other hand, subsurface deposit feeding increased with depth and with percentage of organic carbon. Motile organisms were dominant everywhere, suggesting that motility is important in physically unstable environments (Gaston, 1987).

THE RAVEN RIVER MEMBER-SEDIMENTOLOGICAL PERSPECTIVE

For the Raven River Member two types of subdivision can be applied: 1) the designation of lithofaices, based on unique lithological characters and degree of bioturbation; and 2) ichnofossil assemblages which record the ichnogenera that occur together, whether through contemporaneous formation or overprinting.

The lithofacies and ichnofossils which are present are correlated to each other and final interpetations will be based on these relationships. Two basic subdivisions of litholgy were interpreted: storm and fairweather deposits. In the Cardium Formation, storm-generated deposits encompass very fine, fine sand-sized particles and coarse silt-sized particles. Mud sized material represents fairweather or 'background' sedimentation. These two occur in various proportions in each lithofacies.

To a certain extent, storm-related and background ichnofossils can also be differentiated. These two suites can coexist within an ichnofossil assemblage.

The recogition of relatively large 3-dimensional ichnogenera and bedforms in core is always somewhat subjective. Ichnogenera were considered significant only after being identified in a number of core in various orientations in relation to the core. The work of Chamberlain (1978) was of some benefit in identification. Only small-scale bedforms can positively be identified in core. Identification of hummocky-cross stratification in core seems to be somewhat interpretational and so is discussed following the lithofacies description in the interpretational section of this paper.

Lithofacies

Lithofacies used in this paper are those of Vossler and Pemberton (in review), and lithofacies from that study which do not occur in the Raven River Member are omitted herein. To avoid confusion the term facies is used for different lithologic types while the term assemblage is used to distinguish ichnofossil groups. These lithofacies are primarily refered to by name to distinguish them from numbered ichnofossil assemblages, with the appropriate facies number given in brackets (Plates 4 and 5).

<u>Mudstone with preserved coarse siltstone and fine sandstone laminae to thin beds.</u>(F1)
Siltstone and very fine sandstone beds are wave-rippled to plane parallel laminated. Only very rarely are biogenic structures present in this facies, and these are generally associated with the siltstone and very fine sandstone beds.

Homogeneous mudstone. (F2) This mudstone has less than 10% very fine sand or coarse silt sized particles. Very few identifiable biogenic structures are present but the facies has an overall mottled appearance, suggesting pervasive bioturbation. Bedding is massive and monotonous. Very rarely, thin siltstone beds are present. These may be rippled or plane parallel laminated.

Homogenised sandy mudstone. (F3) A mudstone with 10% to 40% fine to very fine sand-sized particles, which are mixed into the mud by biogenic activity. Identifiable (ie. distinct forms) ichnofossils are common. Rare sharp-based rippled or plane parallel laminated very-fine to fine sandstone beds are present.

Homogenised muddy sandstone. (F4) A very fine to fine-grained sandstone with 40% to 60% mud-sized material. Highly bioturbated with abundant identifiable trace fossils. Mud and sand-sized material are in some areas completely mixed, in other areas a banded appearance persists, indicating that primary deposition consisted of sand and mud interbeds.

Mottled interbeds of sandstone and mudstone. (F5) Individual beds are thin, ie. 1-15 cm. Sandstone beds are fine to very fine grained. Load structures and mudstone clasts are common at the base of sandstone beds. These mudstone clasts are usually disk shaped and are sometimes partially or completely sideritised. Sandstones may be rippled or plane parallel laminated, but biogenic reworking is prominent in most beds.

Interbedded sandstone and mudstone. (F6) Individual beds are thin, and sandstones may be wave rippled or plane parallel laminated. Sandstone beds are fine to very fine grained. Load structures and mudstone clasts are common at the base of sandstone beds. In this facies, physical structures are predominant in the sandstone beds, with biogenic structures present only very rarely. Mudstone beds are frequently unbioturbated as well.

Bioturbated thick-bedded or amalgamated sandstone. (F7) Fine to very fine grained sandstone which occurs in beds which are greater than 15 cm thick. Some of these sandstone units appear to be amalgamated sandstone beds, with scour surfaces present within the unit. Physical structures include wave ripples, plane parallel lamination and gently inclined parallel lamination. Disk shaped mudstone clasts and sideritised mudstone clasts are common at the base of individual beds. Uncommonly, thin mudstone partings are present and these may be bioturbated. While some mottled texture is present, in general bioturbation is confined to discrete structures.

Thick-bedded or amalgamated sandstone. (F8) Fine to very fine grained sandstone which occurs in beds which are greater than 15 cm thick.Physical structures include wave ripples, plane parallel lamination and gently inclined parallel lamination. Disk shaped mudstone clasts and sideritised mudstone clasts are common at the base of individual beds. Rarely thin bioturbated or unbioturbated mudstone partings are present.

Coarsening and thickening upward sequences

A lower coarsening upward sequence seems to be persistent throughout the Pembina area (Plint *et al.*, 1986; 1987; Leggitt, 1987). The upper coarsening upward sequence (of the aforementioned authors) is frequently divisible into two or more smaller thickening (of sandstone beds) and coarsening upward sequences, with the greatest number present in the northwest part of Pembina, in areas where incision at the base of the conglomerate is minimal.

A) Lower coarsening upward sequence

The lower coarsening upward sequence is predominantly comprised of mudstones. Bioturbated mudstones grade upward into interbedded mudstone and sandstones (either bioturbated or unbioturbated) and are capped by a thin, parallel laminated sandstone. In many cases the sandstone at the top of the sequence is very thin, and in some wells it is not present. In these cases, the lower sequence consists of mudstones with increased percentage of sand sized particles in the upper parts. Where it is present the uppermost sandstone is sometimes bioturbated. In some wells (especially to the northwest of Pembina) a 'gritty siderite' (*sensu* Bergman and Walker, 1987 a sideritised mudstone with very coarse to medium sized sand-sized chert grains scattered through it) is developed at the top of the lower sequence.

B) Upper coarsening upward sequence

The upper coarsening upward sequence is much similar to the lower sequence in having mudstones with an increasing percentage of sand-sized particles upward. Above this, the upper coarsening upward sequence displays a complex interlayering of interbedded sandstones and mudstones and thicker sandstones. The occurrence of each such package may represent a smaller coarsening upward sequence, but overall the amalgamated sandstone thickens upward with decreasing bioturbation upwards, reflecting an increase in energy in the system.

Lithofacies interpretatations

Before detailed ichnology is discussed, some conclusions can be drawn from the lithofacies.

The deepest environments of the Raven River Member are probably represented by the mudstone with preserved siltstone beds and the homogenous mudstone (F1 and F2). These facies are differentiated by the degree of bioturbation. While bioturbation was very significant in the homogenous facies, preservation of siltstone and sandstone beds indicate that biological reworking was minimal. Laminated mudstones are frequently associated with reduced oxygen conditions (O'Brien, 1987). In relatively deep marine settings, oxygen is frequently a limiting factor on bioturbation (as opposed to salinity, temperature, etc.) The rareness of F1 in the Raven River Member indicates that for the most part the basin was well oxygenated.

Microfabric may provide further clues about the degree of bioturbation. O'Brien (1987) proposed that unbioturbated shales would display a parallel alignment of clay minerals when examined using S.E.M., and that totally bioturbated shales would have a random alignment of the clay particles. Brief S.E.M. examination of mudstones from the Cardium Formation revealed that mudstones of F1 show alignment of clays, as do unbioturbated mudstones of F6; mudstones of F2 show random orientation of clays. Unbioturbated mudstones interbedded with storm sandstones can indicate either that the storms were so frequent that bioturbating organisms are excluded, or that the colonising organisms affected the sediment only to shallow depths, so that any biogenic structures formed were easily removed by storm scour (refer to the example of Rhoads *et al.*, 1985 cited earlier in this paper).

Gradual increase in sandstone percentage and thickness, with decreasing preservation of bioturbation characterises the other facies of the Cardium. It is probable that sequences of plane parallel laminated sandstone, grading to gently inclined lamination, grading upward into wave ripples represent hummocky cross stratification. The high energy nature of these sedimentary structures in addition to the abundance of shale clasts indicate a storm influence. Since no medium to large scale cross-beds are preserved, there is no evidence of wave reworking above fairweather wave base. Thin sandstone beds present in mudstone units appear to be distal equivalents of thicker amalgamated storm beds.

The facies, as delineated herein, seem to be typical of a distal to proximal hummocky-cross stratification sequence or outer shelf to shoreface sequence (Brenchley *et al.*, 1986; Swift *et al.*, 1987). In a situation of simple stacking of facies F2-F8, a simple prograding storm-dominated shelf setting could be envisaged. However, a more complex interdigitating of facies exists, suggesting that at least small scale sea level changes occurred during Raven River deposition.

THE RAVEN RIVER MEMBER-ICHNOLOGICAL PERSPECTIVE

The most common ichnogenera of the Cardium Formation include *Asterosoma*, *Bergaueria*, *Chondrites*, *Conichnus*, *Cylindrichnus*, *Helminthopsis*, *Ophiomorpha*, *Palaeophycus*, *Planolites*, *Rhizocorallium*, *Rosselia*, *Skolithos*, *Teichichnus*, *Terebellina*, *Thalassinoides*, and *Zoophycos*. Brief descriptions of these forms and photographs are given in chapter two.

From the overall occurrence of ichnogenera (Fig. 4), specific recurring ichnossil assemblages can be discerned. These are summarised in Table 2 and are discussed in detail below.

<u>Assemblage 1</u>: *Chondrites*, *Planolites*, *Helminthopsis* (with rare *Terebellina* and

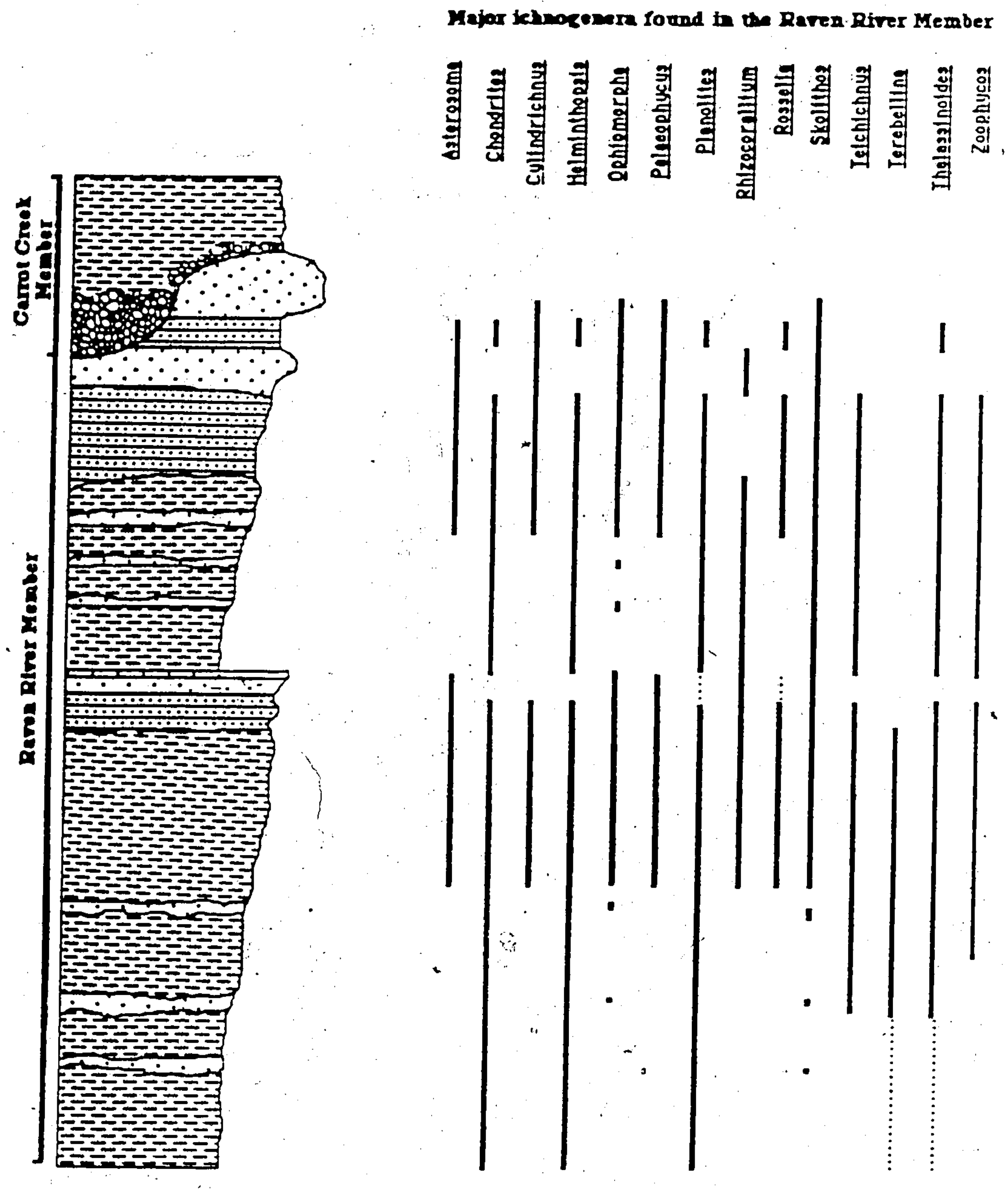

Figure 4. Distribution of important ichnogenera in the Raven River Member. Dotted occurrence lines indicate questionable or rare occurrences.

Thalassinoides). This assemblage is found in massive, monotonously bedded mudstones and mudstones interbedded with sandstones, or occurring as partings. Frequently *Planolites* occurs alone. The limited diversity of this ichnofossil assemblage is likely due to pervasive bioturbation by deposit-feeding organism in an offshore setting with a slow, steady sedimentation rate (Dapples, 1942; Frey and Howard, 1985). In other words, the total ingestion and reingestion of the sediment tends to obscure individual structures. The relative scarcity of deep bioturbation structures is either due to a lack of recognition (no grain size contrast) or more probably to the limited availability of deeply buried nutrients, in relation to shallower resources. Under conditions which allow total shallow working of resources, deep deposit feeding is of little advantage.

A subset of this assemblage is the prolific occurrence of *Chondrites* in mudstones interbedded with storm-generated sandstones. This may be a response to storm burial of organic material which create local anoxic conditions. *Chondrites* behavior allows organisms to overcome, these conditions and take advantage of buried nutrients (Vossler and Pemberton, 1988).

Assemblage 2: *Thalassinoides*, *Terebellina*, rare *Teichichnus*, *Chondrites*, *Helminthopsis*, and *Planolites*. This assemblage occurs in homogenised mudstones and sandy mudstones. It is distinguished by the frequent occurrence of *Thalassinoides*, and the occurrence of *Teichichnus*. *Teichichnus* is rare in the Cardium Formation in the Pembina area, suggesting that this behavior type is not beneficial in areas of slow, steady sedimentation rate, punctuated by high energy scour and deposition events. The frequent occurrence of *Thalassinoides* may be a result of shallowing, and greater abundance of nutrients brought in by storm activity.

Assemblage 3: *Zoophycos*, *Thalassinoides*, *Terebellina*, *Teichichnus*, *Chondrites*, *Helminthopsis*, *Planolites*, and *Skolithos*. The presence of *Zoophycos* and *Skolithos* distinguish this assemblage. *Zoophycos* may be more noticeable here due to increased sand percentage or increased benefits of deep deposit feeding, perhaps because of buried organic material due to higher sedimentation rate. *Zoophycos*, in Mesozoic rocks, is almost always shelfal (Bottjer *et al.*, 1987), and seems to be most abundant in areas with somewhat limited circulation (Ekdale *et al.*, 1984). The increase in *Zoophycos* does correlate with increased amount of dispersed sand-sized material and increased preservation of thin siltstone-sandstone beds, which are probably storm-generated. This may indicate an increase in the degree of deep burial of organic material.

Assemblage 4: *Asterosoma*, *Bergaueria*, *Chondrites*, *Conichnus*, *Cylindrichnus*, *Helminthopsis*, *Ophiomorpha*, *Palaeophycus*, *Planolites*, *Rhizocorallium*, *Rosselia*, *Skolithos*, *Teichichnus*, *Terebellina*, *Thalassinoides*, and *Zoophycos*. This group of ichnogenera is found in sandy mudstones, muddy sandstones, and mottled sandstone/mudstone interbeds. *Asterosoma* and *Rosselia* are both traces of systematic deposit-feeding working from a fixed centre, and are closely related in origin (Chamberlain, 1971). This type of deposit-feeding seems to be associated with sandier substrates, and may be diagnostic of organisms which are able to manipulate slightly coarser-grained substrates. *Skolithos*, *Ophiomorpha* and in some cases *Cylindrichnus* are associated with storm-generated fine sandstone beds. These three ichnogenera are domichnia, the dwelling burrows of suspension-feeding organisms (Vossler and Pemberton, in press). When these traces are present, they are found as relicts present in the sandstone beds, rather than being contemporaneous with the ichnogenera associated with muddier substrates. The appearance of *Palaeophycus* in this assemblage is probably due in some part to the lighter colour of this slightly coarser substrate, allowing discernment of the darker muddy wall lining.

Assemblage 5: *Asterosoma, Rosselia, Ophiomorpha, Palaeophycus, Planolites, Skolithos, Cylindrichnus*. This assemblage is found in the sandstones of the Cardium Formation. It shows a diversity of deposit and suspension-feeding behavior, possibly specialised for dirty fine sand.

A subset of this assemblage is the occurrence of *Skolithos* and *Ophiomorpha* together or alone in amalgamated sandstones. These ichnogenera, in this type of situation, indicate physically unstable (ie. high storm frequency conditions) which favour opportunistic behavior (eg. Rhoads *et al.*, 1985).

Assemblage 6: *Didymaulichnus, Lockeia*. This assemblage is a somewhat artificial grouping based on mode of preservation. These ichnogenera occur only at the base of sandstone beds. Here they are infilled by storm generated sandstones. A possible mechanism for preservation of these essentially surface features is that proposed by Seilacher (1962) for ichnofossils at the base of turbidite beds. The burrows are emplaced and infilled with mud. The bedding plane they are on, and the base of the burrows form a subtle lithologic heterogeneity, along which later storm scour occurs. The burrows are then filled with sand which is deposited in the wake of storm activity (Fig.5).

Assemblage 7: *Skolithos*. This assemblage is found in isolated sandstone beds which are interpreted as storm-generated, or in individual beds in amalgamated sandstone units. *Skolithos* in this assemblage are relatively small (short and narrow), with only very thin

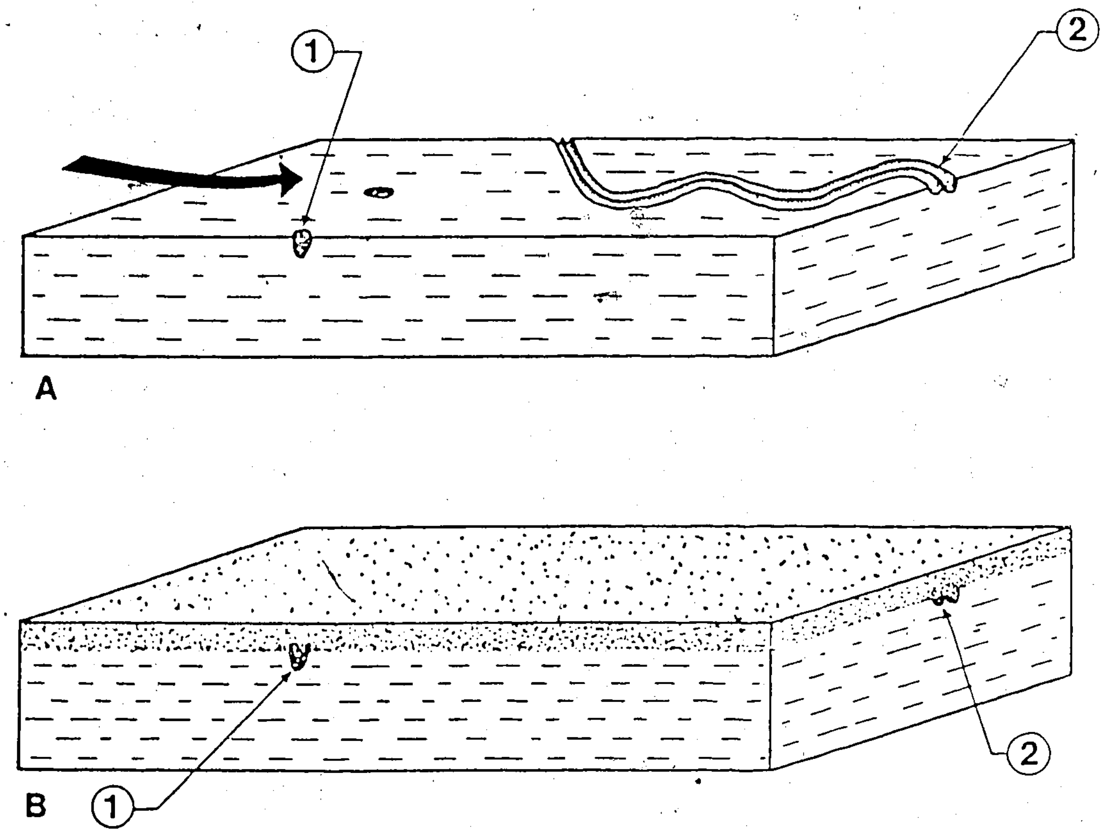

Figure 5. Block diagrams showing the mode of preservation for *Lockeia* (1) and *Didymaulichnus* (2). A. Scouring "cleans" the burrows. B. Infill of burrows with sand deposited in the wake of storm activity.

linings. This assemblage was discussed in some detail in chapter five.

Sequence of burrowing

From examination of highly bioturbated mudstones and sandy mudstones, a sequence of burrowing can be described, based on the burrow wall definition and cross-cutting relationships.

Thalassinoides, *Planolites*, *Palaeophycus*, *Lockeia* and *Didymaulichnus* represent the [illegible] stages of bioturbation. Frequently, these traces have somewhat "fuzzy" walls, [illegible] soupground or close to soupground conditions (*sensu* Ekdale *et al.*, [illegible] burrows thus represent relatively shallow burrowing activity in muds that have not yet been subjected to any dewatering as a result of burial and compaction.

Burrows such as *Teichichnus*, *Asterosoma*, *Terebellina* and *Rosselia* are intermediate in the sequence. *Rosselia* must have been at the sediment/water interface extending into somewhat firmer sediments. These burrows are seldom subject to reburrowing. *Helminthopsis* is possibly an intermediate depth burrower, since it is commonly found within *Planolites* and *Thalassinoides*. *Terebellina* shows some distortion due to compaction.

Zoophycos and *Chondrites* are the deepest burrows in the Raven River Member. *Chondrites* appears to cross-cut all other burrow forms and is thus most likely the deepest burrow of the mudstones. *Ophiomorpha* systems from other localities can be very deep (Frey *et al.*, 1978) but in the core used in this study there was no way to determine the depth to which they penetrated.

Planolites and *Thalassinoides* are frequently reburrowed with *Chondrites* and *Helminthopsis*. Two possible explanations are proposed for this phenomenon: 1) the infill of these burrows is more easily penetrated than the compacted muds surrounding

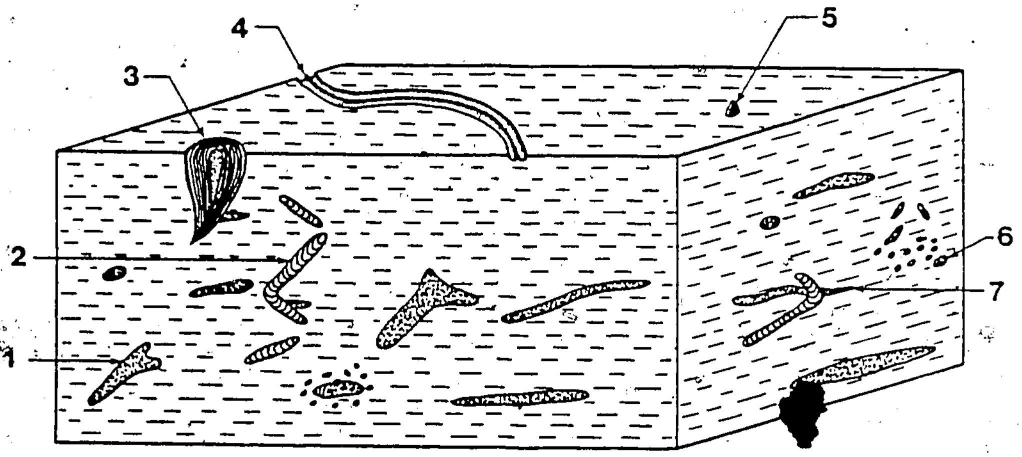

Figure 6. Ichnogenera associated with mudstones and sandy mudstones of the Cardium Formation. 1. *Thalassinoides*; 2. *Zoophycos*; 3. *Rosselia*; 4. *Didymaulichnus*; 5. *Lockeia* (with bivalve in place); 6. *Chondrites*; 7. *Planolites*.

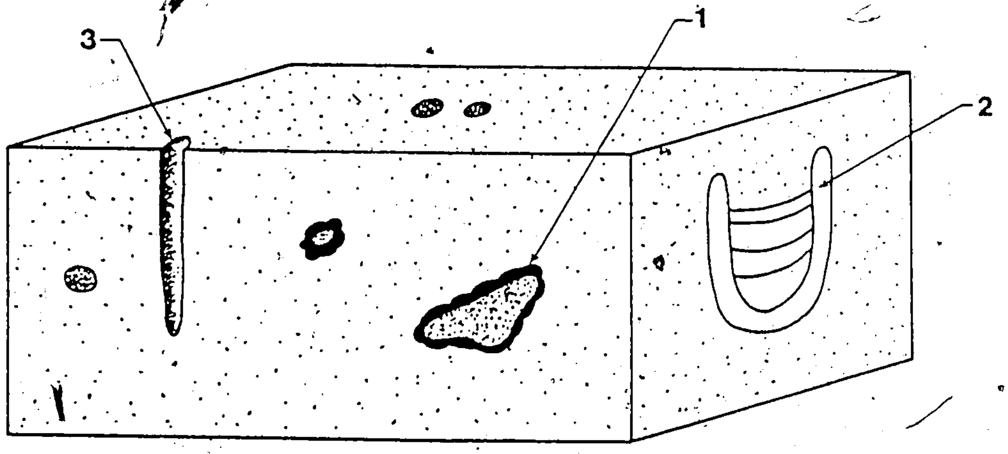

Figure 7. Ichnogenera associated with sandstones. 1. *Ophiomorpha*; 2. *Diplocraterion*; 3. *Skolithos*.

TABLE 2: ICHNOFOSSIL ASSEMBLAGES OF THE CARDIUM FM

Assemblage	Ichnogenera	Behavio
1	*Chondrites*	deep deposit-feeding
	Planolites	deposit-feeding
	Helminthopsis	grazing
	Terebellina	dwelling
	Thalassinoides	deposit-feeding
2	*Chondrites*	deep deposit-feeding
	Planolites	deposit-feeding
	Helminthopsis	grazing
	Terebellina	dwelling
	Thalassinoides	deposit-feeding
	Teichichnus	deposit-feeding
	Palaeophycus	dwelling (suspension-feeding or carnivorous)
3	*Chondrites*	deep deposit-feeding
	Planolites	deposit-feeding
	Helminthopsis	grazing
	Terebellina	dwelling
	Thalassinoides	deposit-feeding
	Teichichnus	deposit-feeding
	Palaeophycus	dwelling (suspension-feeding or carnivorous)

Assemblage	Ichnogenera	Behavior
3 (cont.)	*Zoophycos*	deep deposit-feeding
	Skolithos	suspension-feeding
4	*Asterosoma*	deposit-feeding
	Bergaueria	suspension-feeding
	Conichnus	suspension feeding
	Cylindrichnus	suspension-feeding
	Ophiomorpha	dwelling
	Rosselia	deposit-feeding
	Rhizocorallium	deposit-feeding
	Chondrites	deep deposit-feeding
	Planolites	deposit-feeding
	Helminthopsis	grazing
	Terebellina	dwelling
	Thalassinoides	deposit-feeding
	Teichichnus	deposit-feeding
	Palaeophycus	dwelling (suspension-feeding or carnivorous)
	Zoophycos	deep deposit-feeding
	Skolithos	suspension-feeding
5	*Rosselia*	deposit-feeding

Assemblage	Ichnogenera	Behavior
5 (cont'd)	*Asterosoma*	deposit-feeding
	Ophiomorpha	dwelling
	Palaeophycus	dwelling (suspension-feeding or carnivore)
	Planolites	deposit-feeding
	Skolithos	suspension-feeding
	Cylindrichnus	suspension-feeding
6	*Didymaulichnus*	crawling trace
	Lockeia	resting trace
7	*Skolithos*	suspension-feeding

[1] deep deposit-feeding: ingesting of detritus in areas well below the sediment/water interface where some dewatering of sediments has occurred

[2] deposit-feeding: ingesting of detritus; the organism actively fills the burrow

[3] grazing: systematically moving detritivores, eating continously while moving

the burrows; or 2) the burrows contain abundant fecal material which is nutrient rich (Rhoads, 1974).

Ichnological overview

The ichnofossils of the Raven River member show a mixing of suspension and deposit feeding strategies caused by the interplay of storm and fairweather conditions, and the alternation of mud and sand deposition (Fig. 6, Fig. 7). Diversity of ichnogenera is greatest where mixing of these two seperate strategies is the greatest. Preservation potential is important in determining the ichnocoenoses which are found in these deposits. Deep-burrowing organisms tend create structures which overprint earlier formed burrows of shallow dwelling organisms. This may make deep burrows appear more significant than they actually are in each assemblage. As well, small shallow burrowing organisms may be very important in areas exposed to high stress, but traces of these organisms are easily removed by shallow scour. In the rock record, the evidence of these colonists is lost (Rhoads, 1985).

In addition to diversity of ichnogenera, the Raven River Member shows a diversity of organisms that were present in the shelfal environments. *Ophiomorpha* and *Thalassinoides* can be attibuted to shrimp or shrimp-like organisms; *Bergaueria* and *Conichnus* are generally attributed to burrowing anenomes; *Didymaulichnus* to shallow grazing mulluscs; *Lockeia* and some of the escape traces to burrowing bivalves; *Skolithos* and *Cylindrichnus* to suspension feeding worms; *Rosselia*, *Asterosoma*, and *Planolites* to shallow burrowing deposit feeding worms; *Zoophycos* and *Chondrites* to deep-deposit feeding worms; *Helminthopsis* to grazing worms; and *Palaeophycus* to carnivorous worms (refer to chapter 2).

PALAEONTOLOGY

Body fossils are extremely rare in the Cardium Formation in subsurface. While assorted, poorly preserved speciments of *Inoceramus* sp., *Baculites* sp. and unidentified ammonites were found in the mudstones of the overlying Carrot Creek Member, almost no shell debris was found in the Raven River Member. This is undoubtably due to the great influence of bioturbating organisms in the Raven River Member (Brett and Baird, 1986). Hard shelled organisms were undoubtedly present, as evidenced by the occurrence of burrows associated with bivalves such as *Lockeia*. Rare molds of bivalves were found at the base of storm beds, with the shell completley leached away. These shells probably represent a storm lag (Kreisa and Bambach, 1982). Their position at the base of a sandstone protected them form the actions of bioturbating organisms.

TAPHONOMY AND EARLY DIAGENESIS

The highly bioturbated nature of the Raven River Member does not favour preservation of body fossils. Bioturbating organisms disrupt and in some cases ingest buried organic material, such as shells. As well, intense bioturbation can increase the depth of oxygen penetration into the substrate, and increase the permeability of muddy sediments (Rhoads, 1974). In a $CaCO_3$ undersaturated environment, these factors would tend to favour dissolution of shell material.

A relatively rapid sedimentation rate, burying uningested organic material is suggested by the presence of abundant siderite concretions. Frequent storm- deposition could easily bury decaying matter below the depth of bioturbation to trigger siderite formation. Concretion growth has protected some burrows from compaction, allowing dimensions closer to the primary burrow size to be recorded (Baird *et al.*, 1986).

Pyrite is common in burrow fills and may have formed where decaying fecal material caused local reducing conditions necessary for its formation (Ekdale *et al*, 1984).

DISCUSSION

Based on the above description and evaluation of various lithological, palaeontological, and ichnological elements, a model synthesizing these elements can be assembled.

At a large scale, the depositional system of the Raven River Member of the Cardium Formation in the Pembina oilfield can be deduced using broad lithological and ichnological characteristics. The absence of any medium or large scale cross bedding and any grain sizes greater than fine sand suggest deposition below fairweather wave base. Indeed, the absence of any cross bedding is what distinguishes the Cardium Formation from most of the shelf ridges descibed earlier. The degree of bioturbation and the types of traces present support an offshore, below normal wave base interpretation. The 1-3 thickening upward sandstone sequences seem to be part of a overall thickening upward sequence, which is punctuated by periods in which aggradation slowed. The complex interplay of subsidence (controlled by tectonic activity in the rising Cordillera), sedimentation rate and eustacy was responsible for these thickening upward cycles, which represent a punctuated rise in sea-level (parasequence-*sensu* Mitchum *et al.*, 1977). While some workers believe that eustatic (i.e. globally correlatable) sea level changes are most significant in Cardium deposition (D. Cant, 1988, pers. comm.), the present authors propose that Cardium deposition must have been influenced by local tectonic events. As well, the problems of definitely correlating small scale fluctuations of sea level on a world level makes eustacy difficult to prove. Collision and uplift in the western parts of the Cordillera may have caused increased thrusting to the east. Thrust faulting has been found to be associated with downwarping and subsidence in the foreland basin, and if sedimentation rates fail to keep pace with this subsidence, then sea level rises (Beaumont, 1981; Kauffman, 1984). The thickening upward sequences thus represent periods of rapid sea level rise (lower mudstones and grits) followed by shoaling as the basin fills. 'Gritty siderite' deposits observed in this study and by Bergman and Walker (1987) and Leggitt (1987) represent transgressive lag deposits. The multiple thickening upward sequences may be represented farther offshore by fewer sequences, as distal parts of the basin are less influenced by subtle changes than proximal areas (Kauffman, 1984) (Fig. 8).

The repetition of lithologies and ichnofossil assemblages within the seperate thickening upward sequences indicates a return to conditions analogous to previous conditions. In other words, minor sea level fluctuations allowed a repetition of conditions within an overall shoaling upward sequence.

Lithologically, the Raven River Member shows an increased thickness of parallel laminated to wave-rippled sandstone upwards. These sandstones alternate with mudstones displaying varying percentage of sand and various degrees of bioturbation. The increased percentage of sandstone shows that a greater number or thickness of storm generated sandstone beds have been mixed with the background sediments (mud) by the activities of benthic organisms. Increase in the number of storms that influence the bottom due to shallowing allows the formation of interbedded sandstones and mudstones. As shoaling progresses, storm-generated sandstones become thicker, and bioturbating organisms are less able to churn through them, thus overall mottling of sediments decreases. In amalgamated sandstones, only thin shale partings attest to periods of background sedimentation. The periods of quiessence must have been fairly

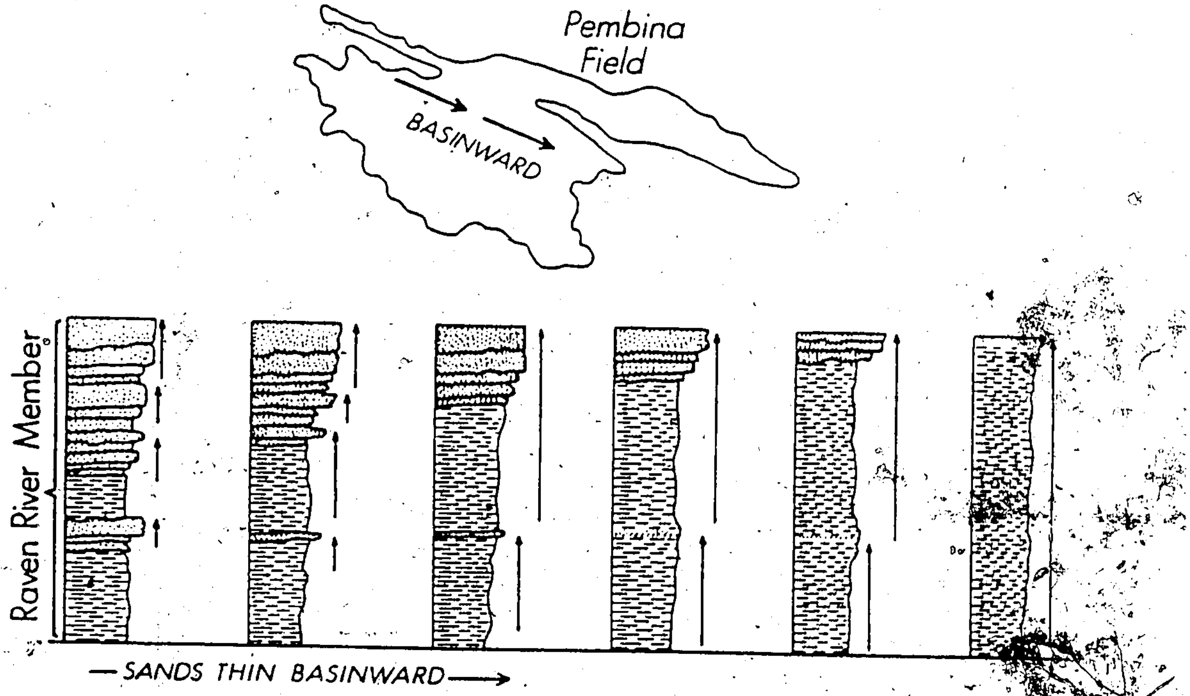

Figure 8. Diagram showing idealised sections (NW-SE) of the Raven River Member showing how the sands thin basinward.

prolonged, since some of the partings show evidence of deep and extensive bioturbation (in the form of *Chondrites*, *Thalassinoides* and *Planolites*), which must have taken some time to establish. Relatively large amounts of sediment must have been removed prior to sandstone deposition, since only the distal portions of the burrows are preserved.

In the bioturbated sandy mudstones, the increased percentage of sandstone alters the texture of the substrate, thus altering the types of behaviour used to exploit this sediment. For example, in sandy mudstones, *Asterosoma-Rosselia* style deposit feeding is more abundant, suggesting that in this slightly coarser substrate this type of deposit feeding is more efficacious.

Large scale correlation of the sandstone/mudstone beds of the Cardium Formation can be done using gamma-ray and spontaneous potential well log data, and core data (see Leggitt, 1987 and Krause *et al.*, 1987). However, bed to bed correlation is difficult. The irregular nature of individual storm beds (and associated muds) is due to the ability of a storm to scour in one area and deposit sediment in another. When examining the specific paleoecology of the Cardium Formation, a more appropriate scale is on a bed to bed level, as storms have the ability to dramatically change the lebensspuren (Pemberton and Frey, 1984; Vossler and Pemberton, in press). In discussion of the fairweather community, deep and shallow burrows can be distinguished. Burrows such as *Planolites*, *Palaeophycus*, *Rhizocorallium*, and generally *Thalassinoides* represent shallow burrowing activities and thus can be taken as indicative of sedimentation conditions at the time of deposition. Deeper burrows such as *Zoophycos* and *Chondrites* may have originated in later deposited beds up to several decimeters above the strata in which they occur. Thus, *Zoophycos* burrows which cut a storm sandstone are probably associated with an overlying horizon (which may have been removed by small-scale erosion). On the other hand, a *Skolithos* at the top of the same storm-generated sandstone can be assume to have been emplaced relatively soon after deposition.

The emplacement of each sandstone bed represents a disruption of the muddy shelfal community. Scour prior to storm generation can redistribute or kill shallow-dwelling benthos. The deposition of several centimeters of sandstone onto the seafloor is also a crisis for the bottom community. It removes burrowing organisms from their optimal dwelling depth below the sediment/water interface. The ability to escape from the blanket of sediment, i.e. burrow up through it, determines if the community can quickly reestablish itself. This ability is strongly related to the type of substrate which buries the organisms. The large number of fugichnia found in the sandstone of the Cardium Formation indicates that many organisms were able to survive minor and relatively severe sedimentation events. As storms become more and more frequent, it is possible that conditions favoured more robust organisms that would be able to repopulate quickly after decimation (Pemberton and Frey, 1984; Vossler and Pemberton, in press). Thus a gradual change in behavior is seen vertically throughout Cardium Formation sequences. As well, subtle textural changes may have helped to alter the benthic community, to a certain extent at least, excluding organisms unable to tolerate sandier substrates.

Rapid storm burial could remove nutrient-rich sediments from the reach of shallow-burrowing deposit-feeding organisms. These buried sediments may not have been completly depleted of their resources prior to burial, and as well the death of some benthic organisms by suffocation would serve to enhance the organic content of the muds. Deep deposit-feeding strategies, such as those represented by *Chondrites* and *Zoophycos*, may have enabled certain organisms to exploit these nutrient-rich areas. The *Chondrites* behavior especially, appears to have enabled organisms to tolerated slightly anoxic conditions such as those created by the decay of organic matter (Bromley and Ekdale, 1984). This idea has been proposed to explain abundant *Chondrites* in interbedded sandstone and mudstones (Vossler and Pemberton, 1988).

The mixed nature of Cardium sandy mudstone ichnofossil assemblages, to a large extent, is a result of preservational mixing and biases. Thin mudstone beds, densely packed with small burrows can represent a far greater amount of time than sandstone beds with a few larger and distinct forms, and for this reason the importance of the sandstone inhabiting forms tends to be overemphasized. As well, higher up in the sequence, the removal of almost all mud gives the impression of a totally sand-dominated environment which may not be correct. Diverse mud-dwelling communities may have been present, but evidence for them has been removed by storm scour.

Evidence for the activities of surface-dwellers are almost completly lost under normal mud sedimentation conditions. Burrows of these organisms are generally buried and then obscured by later bioturbation. The storm dominated nature of the Cardium Formation provides a unique format for preservation of delicate traces. Surface traces such as *Didymaulichnus* and *Lockeia* are infilled with fecal material or mud, and will represent a lithological discontinuity, and thus a boundary for storm scour following burial and compaction. After the storm, burrows are infilled with sand. This is analogous to the mechanism for preserving delicate burrows at the sole of turbidite beds as proposed by Seilacher (1962).

In the amalgamated sandstone beds, the traces of colonising organisms may be removed by storm scour, giving the beds a unbioturbated appearance. Modern studies show that in general, organisms in areas with a high frequency of disturbance are small, and shallow burrowing. As a result, they affect only a small amount of the sediment, and traces of them are easily obliterated (Rhoads *et al.*, 1985, Cuomo and Rhoads, 1987).

In the Raven River Member conditions at the sediment/water interface can be interpreted as well-oxygenated. The abundance of deep and shallow biogenic structures attests to this conclusion, as does the evidence of shelly benthos, which would normally not occur under dysaerobic conditions (Rhoads and Morse, 1971). Local dysaerobic conditions may occur below the sediment/water interface due to decay of buried organic material. The common siderite concretions in the Raven River mudstones indicate that relatively abundant decaying organic material was buried by newly deposited sediment. The occurrence of superabundant *Chondrites* has been shown to be linked to buried organic material (Vossler and Pemberton, 1988) and it is possible that *Chondrites* reburrowing *Thalassinoides* may be consuming decaying fecal material which is causing local dysaerobic conditions.

CONCLUSIONS

The Raven River Member has sedimentological characteristics typical of offshore storm dominated deposits. It is unique, however, in having a prograding shelfal sequence which is not capped by sandstones which show reworking above fairweather wave base. In other words, no medium to large scale cross-bedding is present. The pattern of coarsening upward sequences can be explained by pulses of sea level rise, followed by basin infilling and shoreline progradation.

Physical instability of the environment of deposition was the primary parameter controlling ichnofossil distribution in this shelfal setting, creating ichnofossil assemblages which show a mixing of pre- and post-storm components. Dysaerobic conditions created by sorm burial may have allowed only deep burrowing organisms to exploit nutrients below the sediment/water interface, as evidenced by the prolific Chondrites in interbedded sandstones and mudstones. Evidence for opportunistic recolonisation of storm-generated sandstones has also been preserved in the Raven River Member.

Storm scour, while undoubtedly removing a significant portion of the initial ichnofossil record, has allowed the prervation of *Lockeia* and *Didymaulichnus* in the Raven River Member.

In establishing and comparing ichnological models, the preservational biases towards storm-generated beds and large discrete ichnofossils must be taken into account, especially in outcrops where fairweather beds may be partially destroyed by weathering.

The Raven River Member provides an interesting example of the ichnology of storm-dominated shelfal environments. With increased interest in the hydrocarbon potential of this type of enviroment, a more thorough understanding of the ichnology is important academically and economically.

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CHAPTER FOUR: A FIRMGROUND ICHNOFAUNA IN THE CARDIUM FORMATION (UPPER CRETACEOUS): EVIDENCE FOR LOCAL CHANGES IN SEA LEVEL

INTRODUCTION

The ichnology of discontinuities with firm but unlithified substrates at the time of excavation has only rarely been documented in the rock record. Such a surface is present in the Upper Cretaceous (Turonian) Cardium Formation in the Pembina and Carrot Creek oilfield areas of west central Alberta, Canada (Fig.9). In the core examined, the Cardium Formation consists of several coarsening upward sequences of mudstone and sandstone unconformably overlain by conglomerate. Where present, the firmground ichnofossils discussed in this paper are found at the base of the conglomerate. The nature of this contact and the genesis of the conglomerate has been a source of speculation and research since the discovery of the Pembina oilfield in 1953 (Nielsen and Porter, 1984). Recent work on the Cardium Formation (Plint *et al.*, 1986; Bergman and Walker, 1987; Leggitt, 1987) indicates that the base of the conglomeraate may represent a depositional sequence boundary (*sensu* Mitchum *et al.*, 1977). If this is the case the conglomerate is unrelated to the underlying sandstone and the base of the conglomerate is an unconformity surface representing erosion of strata during a maximum lowstand of sealevel.

Firmground identification has been critical in identifying sequence boundaries in areas close to the Atlantic passive margine examined by Vail *et al.* (1977) (Kidwell, 1984), and may be of great benefit in defining sequences away from the Atlantic. In areas where lithological changes at sequence boundaries are subtle, firmground identification may be the only evidence for sequence boundaries.

The Cardium Formation with the underlying Blackstone Formation and the

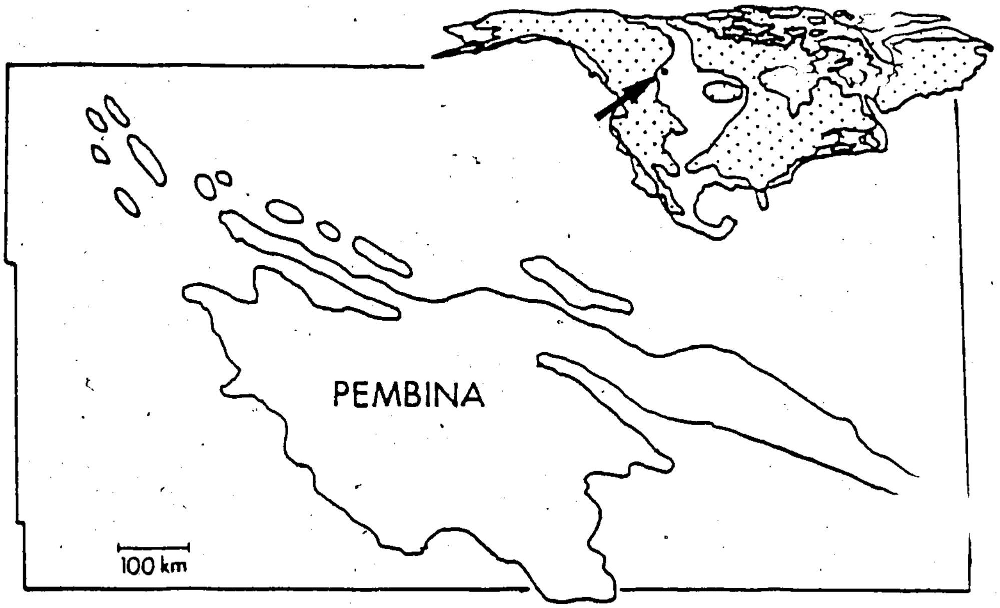


Figure 9. Pembina oilfield area and its approximate position in the Western Interior Seaway of late Turonian time. (modified from Walker, 1986 and Barron, 1987)

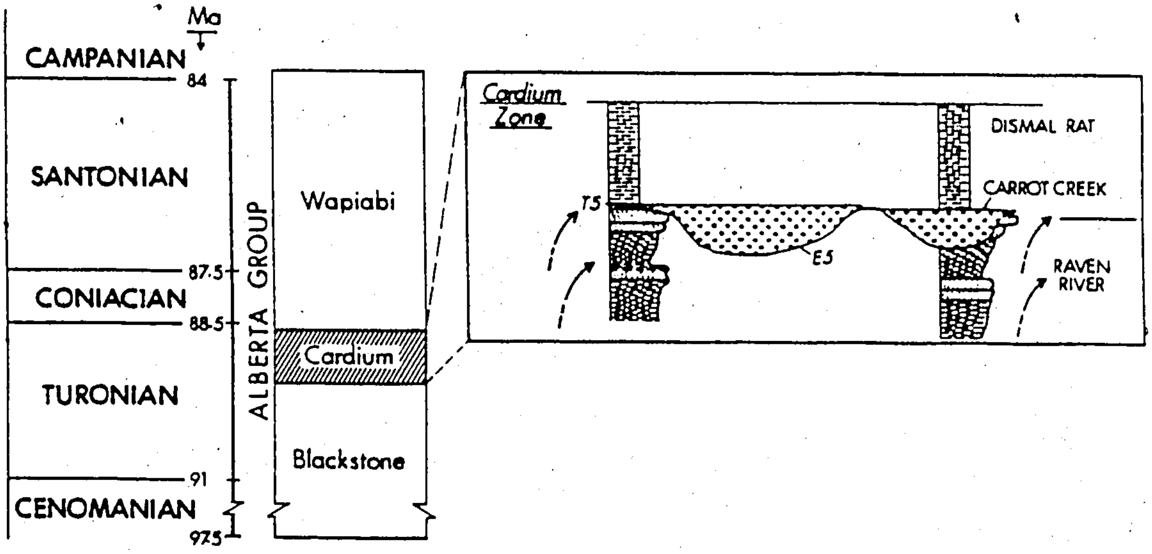


Figure 10. Stratigraphy of the Cardium Formation. Right inset shows the Carrot Creek area on the left and the Pembina area on the right. (modified from Plint *et al.*, 1986)

overlying Wapiabi Formation comprises the Alberta Group in subsurface (Fig. 10). The occurrence of coarsening upward sequences capped unconformably by conglomerates, having total thicknesses which range from metres to centimetres, is ubiquitous to the Cardium Formation (Plint *et al.*, 1986). In the most recently proposed subsurface stratigraphy, the Cardium has been divided into members based on the presence of unconformity surfaces overlain by a conglomerate (Plint *et al.*, 1986). Erosion surfaces at the base of conglomerates are interpreted as representing lowstand of sealevel and the top of the overlying conglomerate represents a transgressive surface.In core from Pembina, the Cardium is comprised of the Raven River Member, which consists of a series of sandstone and mudstone coarsening upward cycles; and the Carrot Creek Member, which consist of conglomerates and mudstones (Fig. 10). The base of the thick conglomerate at Carrot Creek has been traced through the Pembina-Carrot Creek area, where the base of the conglomerate was designated equivalent to the E_5 erosion horizon of Plint *et al.* (1986). More recently, Leggitt (1987) used a numerically large database to document topography along the E_5 surface in the Pembina-Carrot Creek area. Several ridge and bevel features were delineated which are thought to represent shoreface erosion of shelfal sediments at the time of a sea level lowstand (Fig. 11). At this unconformity surface, "E5", a suite of ichnofossils has been documented which was formed in firm but unlithified substrates. In this paper, this suite will be described and its significance to sea level changes and sequence boundary delineation discussed.

SEDIMENTOLOGY OF THE RAVEN RIVER MEMBER IN THE STUDY AREA

In the study area, the Raven River Member consists of one or two coarsening

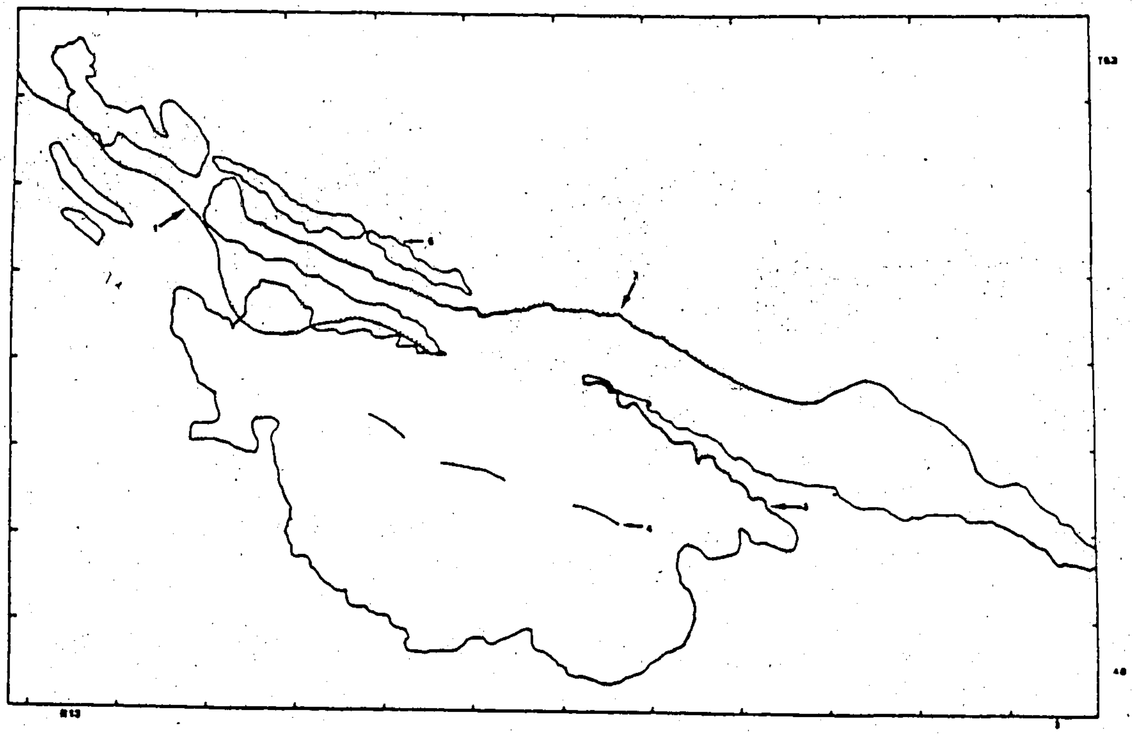


Figure 11. Bevel surfaces in the Cardium Formation. 1. Carrot Creek Bevel; 2. Northern Bevel; 3. Poplar Valley Bevel; 4. Buck Creek Bevel; 5. possible bevel north of Bigoray. Terminology of Leggitt, 1987. (modified from Leggitt, 1987).

upward sequences. Generally, the upper sequence consists of pervasively bioturbated mudstone coarsening upwards into sandy mudstone or muddy sandstonewhich is capped by interbedded sandstone and mudstone. Uppermost in the sequence are thick bedded fine sandstones. The lower coarsening upward sequence is similar, however the thick sandstones are generally absent. Primary siderite nodules are commonly found, as they are throughout the Cardium Formation (Bartlett, 1987). The ichnology and sedimentology of the Raven River Member suggests deposition below fairweather wave base in a storm dominated environment (Vossler and Pemberton, in preparation; Vossler and Pemberton, 1987). The thickness of the Raven River Member may be dependent on the depth of erosion prior to conglomerate deposition, as well as the initial depositional thickness (Leggitt, 1987; Vossler and Pemberton, in preparation).

FIRMGROUND ICHNOLOGY - BACKGROUND

Seilacher (1967) proposed that recurring ichnofossil groups - "ichnofacies" resulted from the interaction of various environmental parameters which were predominantly dependent on bathymetry. In Seilacher's scheme, the *Glossifungites* ichnofacies was comprised of ichnofossils found in nearshore areas where firm but unlithified sediments are exposed by erosion. More recent work has defined the *Glossifungites* ichnofacies as characteristic of semiconsolidated sediments in a marine or nearshore setting irrespective of depth (Pemberton and Frey, 1985). Firmgrounds may develop in both siliciclastic and carbonate substrates, but have never been recognised in nonmarine settings.

In areas with semiconsolidated substrates, organisms tend to construct permanent domiciles. Burrow walls are sharp and the semicohesive substrate makes burrow lining unecessary. Firmgrounds are associated with sedimentation discontinuities and thus burrow fill may differ from the host substrate. Suspension feeders, carnivores and detritus feeders may all colonise firm sediments (Pemberton and Frey, 1985). In ancient sequences, the most commonly found firmground ichnogenera are *Rhizocorallium, Diplocraterion, Skolithos, Gatsrochaenolites*, and *Thalassinoides* (Pemberton and Frey , 1985). Firmgrounds can develop in dewatered muds, partly lithified limestone, and arenaceous sediments that have undergone early cementation. Biogenic structures resembling both burrows (*sensu* Ekdale *et al.*, 1984), and borings (*sensu* Ekdale *et al.*, 1984) can occur under such conditions. A pause in deposition, accompanied by at least shallow erosion, is necessary for firmground development.

Modern examples of firmground burrows have been examined in detail by various authors (Schäfer, 1972; Frey and Basan, 1981; Pemberton and Frey, 1985). All modern examples are found in relatively fine grained sediments such as salt marsh muds, or peats, which may be exhumed by coastal processes in a marginal marine setting.

Examples of interpreted firmgrounds identified in ancient deposits are given in Table 3. These examples can be divided into two basic groups based on substrate type: clastic or carbonate. Although similar ichnofossils are found in both, the diagenetic conditions of their formations are very different. Carbonate firmgrounds most commonly develop through submarine erosion of substrates which were subject to early lithification, thus burial, if it occurred at all, was shallow.

Dewatering of muds is the most common mechanism for firmground formation in siliciclastic substrates. The change in sediment consistency can be observed in the change from indistinctly walled, somewhat deformed burrows associated with softgrounds, to sharp-walled burrows of the firmground suite (Frey and Bromley, 1985). Only very shallow burial may be necessary for firming of the sediment, however, burial

TABLE 3: ANCIENT FIRMGROUND OCCURRENCES

Study	Formation/age	Environment	Lithology	Trace fossils
Kennedy, 1967	Lower Chalk, Mid-Upper Cretaceous	marine	limestone (early lith.)	*Thalassinoides paradoxicus*
Sellwood, 1970	Belemnite marls, Lower Jurassic	marine/ marginal marine	marl-limestone	*Diplocraterion*
Baird & Fursich, 1975	Kuperfels & Gryphacen-bank, Triassic	marine	limestone	*Spongeliomorpha suevica, Diplocraterion parallelum*
Hattin, 1975	Carlisle Fm., Upper Cretaceous	marine	calcarenite	*Thalassinoides, Teichichnus*
Hayward, 1976	Waitakere Grp. Lower Miocene	deep sea	fine grained sediments	*Thalassinoides, Tigillites, Rhizocorallium*
Fürsich *et al.*, 1981	Austin/ Taylor Fm, Upper Cretaceous	marine	chalks (early lith.)	*Rhizocorallium jenense, Spongeliomorpha, Stropichnus xystus, Romulichnus biconites*
Pollard, 1981	Waterstones & lower Keuper marl, Triassic	marginal marine	mudstone	*Diplocraterion luniforme, Thalassinoides suevicus*

Table one continued:

Schroder, 1981	Oconee Grp. Lower Cretaceous-Eocene	marginal	mudstone	*Thalassinoides, Trypanites*
Miller & Rehmus, 1982	Esopus Shale Carlisle Centre Formation, Devonian	marine	mudstone	*Cruziana, Fustiglyphus,* knobs, scratch marks, horizontal and vertical burrows
Kidwell, 1984	Chesapeake Grp., Miocene	marine	sandstone	*Thalassinoides, Skolithos, Gyrolithes*
Bottjer, 1985	Marlbrook Fm., Upper Cretaceous	marine	chalk	*Thalassinoides*
Saunders & Pemberton 1986	Horseshoe Canyon Fm., Upper Cretaceous	marginal marine	sandstone (early lith)	*Diplocraterion*
Landing & Brett, 1987	Hungry Hollow Fm., Middle Devonian	marine	shale/ limestone	*Cruziana, Rusophycus*
[1]Wescott & Utgaard, 1987	Mississipian	marginal marine	sandstone	*Diplocraterion, Rhizocorallium, Teichichnus*

Table one continued:

Savrda & Bottjer, 1987	Monterey Fm., Miocene	marine	siliceous muds & nodular phosphates	*Thalassinoides*
Pemberton p. comm., 1987	Viking Fm., Middle Cretaceous	marine	mudstone	*Skolithos*, *Thalassinoides*
Pemberton p. comm., 1987	Clearwater Fm., Lower Cretaceous	marine	mudstone	*Skolithos*

[1] There is some question about this being a true firmground.

must occur. An important characteristic of all firmground occurrences is the superposition of a new set of burrows upon the original ichnofossils of the softer sediments. The new suite of ichnofossils is created in response to the new environmental conditions existing during or after erosion, therefore the new suite differs in some way from the pre-erosion softground suite. The burrows preserved are almost exclusively the domiciles of suspension feeders.

More rarely, firmgrounds may form in arenaceous sediments by compaction of interstitial clays (Frey and Basan, 1981) or by void filling cementation at shallow depths due to groundwater flow (Saunders and Pemberton, 1986). The latter situation has not been documented in the modern, and is difficult to prove in the ancient record.

EVIDENCE FOR EROSION AT THE BASE OF THE CONGLOMERATE

The major lines of evidence for erosion at the base of the conglomerate are a) topography along the contact and the nature of the contact, b) the types of biogenic structures associated with the contact and c) the interpreted depositional environment above the contact.

A) Nature of the unconformity surface

As demonstrated by detailed well log correlation, the base of the conglomerate ("E_5" surface of Plint *et al.*, 1986) has been shown to have considerable topography (Plint *et al.*, 1986; Bergman and Walker, 1986, 1987; Leggitt, 1987). This explains in part why the base of the conglomerate surface cuts into mudstones, interbedded sandstones and

Plate 6. A. Sharp contact at the base of the conglomerate (8-4-50-8W5M); B. *Thalassinoides* system developed at the base of the conglomerate(4-13-51-11W5M); C. close up of branch in a *Thalassinoides* tunnel(12-14-51-11W5M); D. *Thalassinoides* at base of conglomerate(4-13-51-11W5M). All scale bars are 1cm; bracketed locations are according to Dominion Survey of Canada.

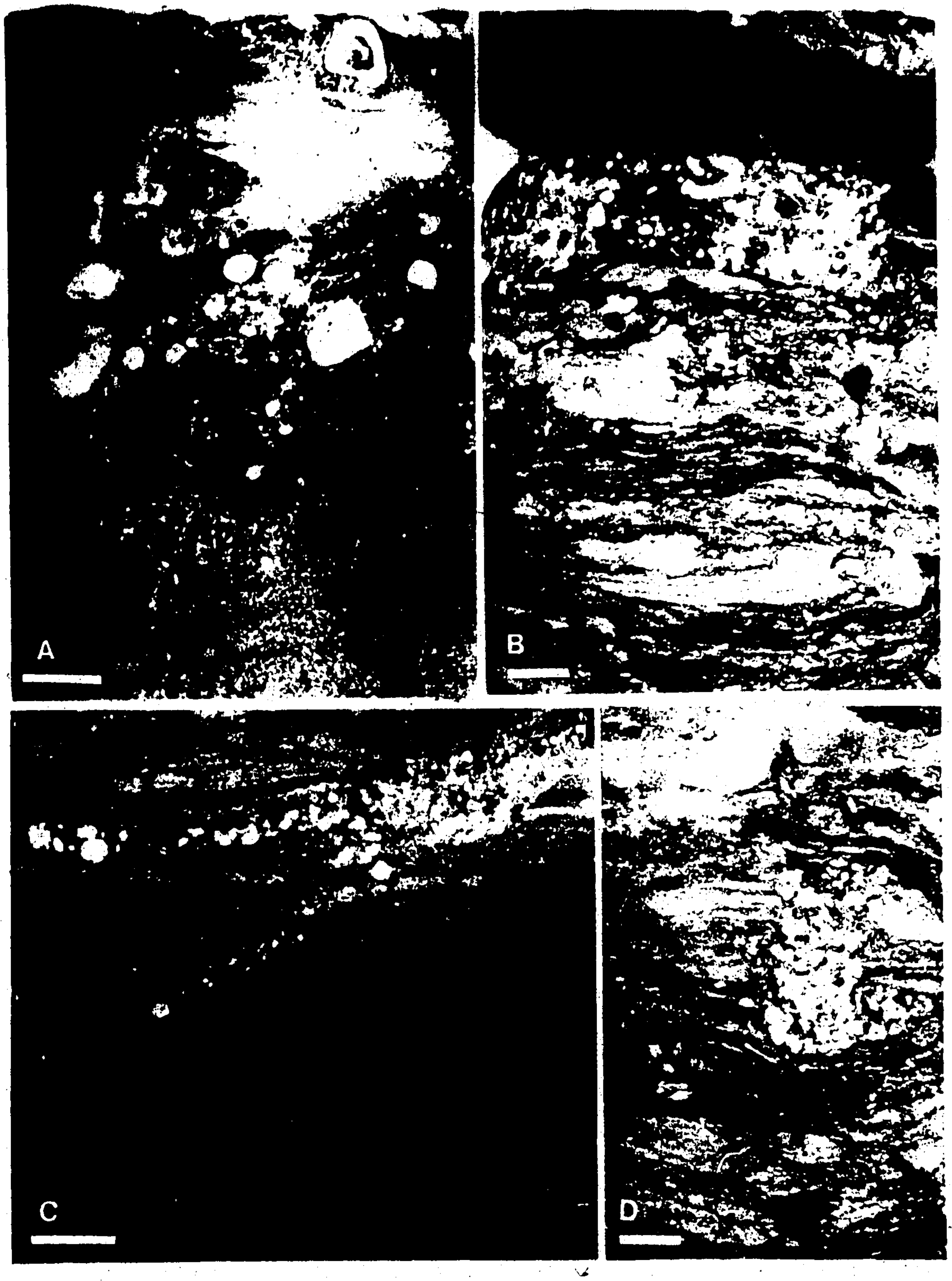
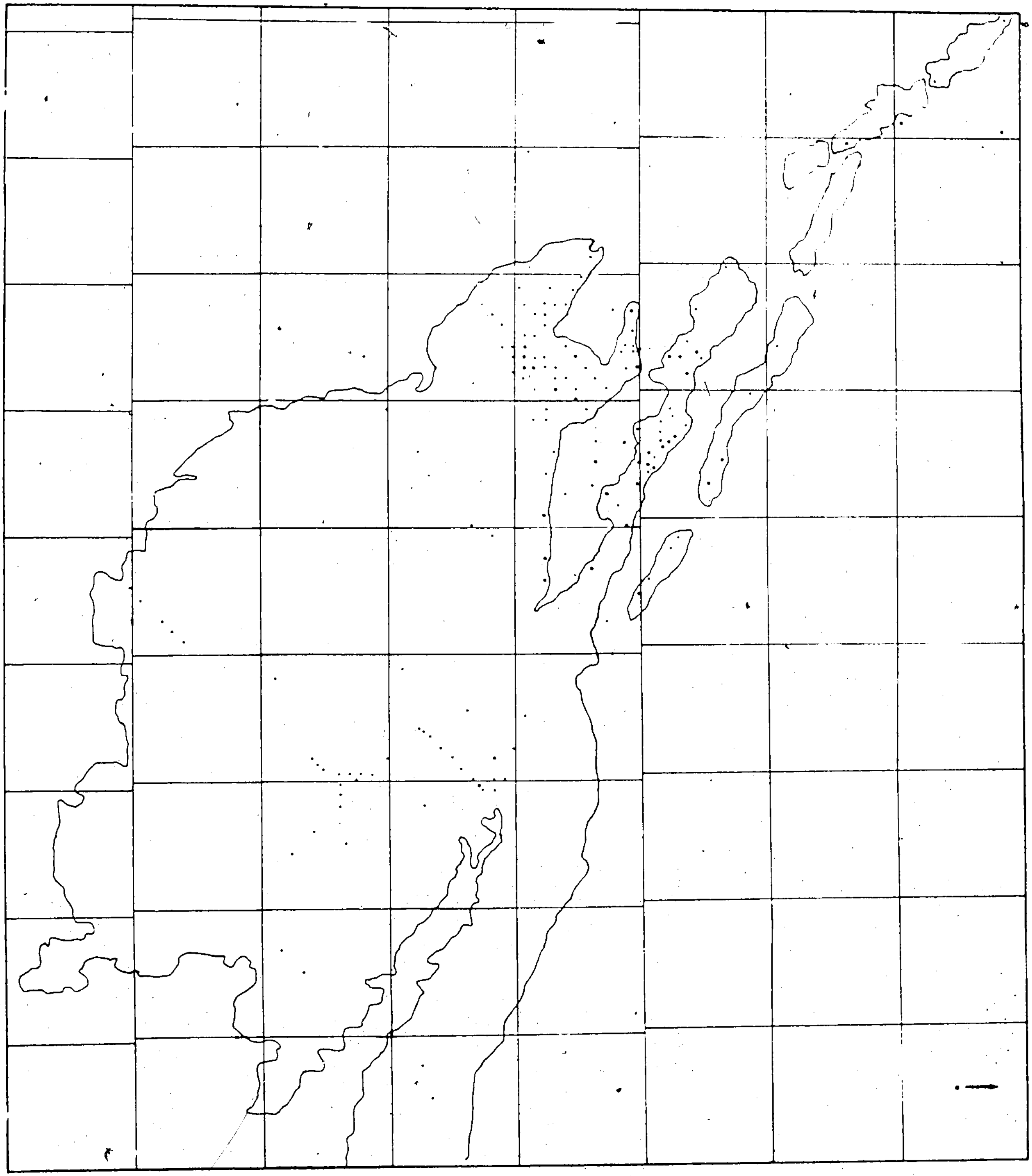

A
B
C
D

Figure 12. Map of the Pembina oilfield area showing the core examined during this study. Crosses indicate contact not visible, open circles indicate sharp contacts, dark circles indicate bioturbated contacts.



mudstones, and sandstone beds. The 'E5' surface has been found to be ubiquitously erosional, but diagenetic evidence from many subsurface areas examined by Bartlett (1987) indicates that underlying strata were only partially lithified at the time of erosion. Examination of the "E5" surface for this study confirms this observation for the Pembina area.

The morphology of the conglomerate's base in the northern part of the Pembina field was documented by Leggitt (1987) in a series of cross-sections and a three-dimensional mesh diagram. A series of ridges and hollows were defined with the hollows representing broad valleys with steep north-east facing slopes (Fig. 11). A broad "plain" exists over most of southern Pembina (Leggitt, 1987).

Three types of contact are found at the unconformity surface (Plate 6): 1) sharp; 2) 'disturbed' contacts; and 3) bioturbated contacts (Fig. 12). Sharp contact are most common; conglomerate-sandstone contacts are sharp and all contacts at the base of thick conglomerates are sharp regardless of the underlying lithology (Fig. 4). Such contacts indicate that the sediments were relatively cohesive prior to conglomerate emplacement. More rarely, contacts were 'disturbed' with some of the sandstone stirred into the conglomerate and mudstones above the contact. In these cases (which were [illegible]) the sandstone may have been unconsolidated at the time of conglomerate deposition. Contacts with biogenic structures are discussed in the following section.

B) Biogenic structures at the E_5 contact

Three types of biogenic structure have been distinguished at the E_5 contact: (1) deep horizontal/subvertical/vertical networks assigned *Thalassinoides*; (2) shallow horizontal burrows, sometimes network-like also assignable to *Thalassinoides*; and (3) shallow subvertical burrows. *Thalassinoides* is the most prominent and distinct ichnofossil in the northern Pembina firmgrounds.

Large *Thalassinoides* systems at the contact are found penetrating into thick sandy mudstones only. *Thalassinoides* networks are the deepest burrows below the contact, penetrating to depths of ~20 cm. Both horizontal and vertical components ae present, but overall system morphology is indiscernible. The burrows are sharp walled with diameters of ~1-2 cm. (Fig. 5). The fill is structureless pebbly mudstone and is interpreted as passive. *Thalassinoides* has been most frequently attributed to the activities of burrowing crustaceans - generally shrimp or lobsters (Häntzschel, 1975; Pemberton *et al.*, 1984). Larger crustaceans are not only capable of excavating firm substrates, they can also manipulate coarse material, such as small pebbles. In firm substrates, cheliciped scratch marks are often present on the interior of burrow walls. In the core examined, no scratch marks were observed, however, weathering usually serves to enhance scratch marks; core does not have this advantage.

Shallow horizontal burrows are frequently found running along mudstone beds in the interbedded sandstone and mudstone units. These burrows are less distinct than the large *Thalassinoides*, perhaps due to color similarities between the fill and the encasing mudstone. The relationship of the burrows suggests interconnection, thus these burrows are also assigned to *Thalassinoides*.

More rarely short vertical burrows are found at the base of the conglomerate. These burrows cut into all lithologies. They are generally found to a depth of <5-6 cm into the underlying lithologies at a slight angle to the contact. The burrows frequently taper very slightly to their base and have sharp walls. These burrows are most probably assignable to the ichnogenus *Skolithos*, which in a firmground environment is most likely the dwelling burrow of a large jawed polychaete similar to the modern worm *Nereis* (Pemberton and Frey, 1985).

C) Sedimentology and ichnology above the unconformity

Three basic lithologies are found above the unconformity: conglomerate or pebbly mudstone; pebbly and sandy mudstone which is bioturbated; and parallel laminated mudstone. More rarely sandstone beds (frequently with pebbles) are found interbedded with conglomerate.

Conglomerate can be matrix or clast supported . In the wells examined in the Pembina area (although the situation is different at Carrot Creek- see Bergman and Walker, 1987) clast supported conglomerates are more rare. Mud supported conglomerates to pebbly mudstones are predominant. Very few of the wells show any definite graded beds. The scale of core in relation to bedforms makes structures such as crossbeds indiscernible. Frequently, conglomerate is confined to a 1-2 centimetre pebbles veneer. Less commonly matrix supported conglomerate have sand to granule sized matrix material.

Pebble lithology is predominantly chert, in addition to sandstone, quartzite, and metamorphic rock fragments. Locally derived angular clasts of siderite, shale and sandstone are common. Large blocks (4-5 cm long axis) of sandstone and mudstone similar to the Raven River Member sediments are also common. Rarely, these mudstone clasts have *Chondrites*, which is also common in siderite clasts found in the conglomerate. In one instance *Zoophycos* was found in a mudstone clast. These clasts are similar to nodules which characterise the Raven River Member . Evidence for local derivation of these siderite clasts is: (a) the large size of the clasts, precluding a distal origin, and (b) simiarity to siderite nodules in the underlying Raven River Member. Preservation of uncompressed burrows within clasts indicates that these siderite clasts were derived from primary siderite nodules (Baird *et al.*, 1986). Bartlett (1987) did an extensive study of the siderite clasts and found that the nodules were still soft when eroded. Siderite in the Cardium Formation is for the most part primary and probably formed at shallow depths (<10 m) (Bartlett, 1987; Gautier and Claypool, 1985). The period of burial could have been relatively short, and erosion relatively shallow for firmground exhumation.

Leggitt (1987), Bergman (1986), and Bergman and Walker (1987) have examined the nature of the conglomerate in the Carrot Creek- Pembina area in some detail. The observations made during this study confirm the sedimentological conclusions of these workers. When present, well sorted clast-supported conglomerate always occurs directly above the erosion surface, and may coarsen upward into more poorly sorted conglomerate (Leggitt, 1987). Pebbly mudstones and mud-supported conglomerates either directly overlie the unconformity or overlie clast-supported conglomerate (Leggitt, 1987). When present, mudstones with large unsorted pebbles are always directly above the unconformity surface (Leggitt, 1987).

In the Pembina area, the conglomerates are most frequently overlain by black mudstones with preserved sharp-based siltstone and very fine-grained sandstone beds. These beds are wave rippled or parallel laminated, and may represent distal storm deposits as described by Hurst and Pickerill (1986). These mudstones are highly fissile and have few identifiable trace fossils, which may be evidence for little biogenic rewoking of the mudstone (O'Brien, 1987). This lack of bioturbation may be due to dysaerobic conditions in a deep outer shelf setting (Ekdale, 1985). Commonly, chert pebble stringers are found within this mudstone. In wells that have extensive core above the unconformity surface, a homogenous black, monotonously bedded mudstone with no identifiable biogenic structures occurs. These mudstones probably represent the deepest depositional environment found in the Cardium Formation at Pembina.

In some wells, the lower portions of the parallel laminated mudstone are bioturbated and contain up to 30% very fine sand-sized particles. These mudstones may be homogenised by bioturbation in some areas and tend to pass upward into parallel laminated mudstones. This trend may represent a gradual deepening upward. A similar trend was linked to a gradual decrease in oxygen level by Savrda and Bottjer (1986), however more independent evidence is necessary before this can be shown in the Cardium Formation.

In the Pembina oilfield area, sandstones interbedded with the conglomerate are rare, although this situation may be more common in the Carrot Creek oilfield. These sandstones are fine to medium grained and may contain chert pebbles. Some medium-large scale cross beds are also present.

Three general ichnofossil assemblages can be delineated in strata above the conglomerate: *Ophiomorpha* which occurs rarely in the sandstones; *Skolithos, Zoophycos, Helminthopsis, Planolites, Terebellina, Chondrites, Thalassinoides, Palaeophycus, Asterosoma, Teichichnus, Rhizocorallium, Rosselia,* and fugichnia found in mottled sandy mudstones with scattered pebbles; and *Planolites* and *Helminthopsis* found in mudstones with preserved sharp-based silt laminae.

Sandstone beds above the contact are very rarely bioturbated so little can be concluded from their ichnology. The bioturbated mudstone suite is similar to those found in the Raven River Member. The abundance, degree of bioturbation, and diversity of traces in conjunction with the behavior represented (predominantly deposit-feeding traces) suggests offshore conditions below fairweather wave base (Vossler and Pemberton in preparation). The third suite is indicative of conditions of deeper water conditions (Vossler and Pemberton in preparation). In some cases the mudstone with sharp-based silt laminae is overlain by a massive mudstone which may represent the deepest environment found in the Cardium. All lithologies above the E_5 contact (with the exception of the massive mudstone) have scattered pebbles.

DISCUSSION - FIRMGROUND CHARACTERISTICS

Bioturbated contacts display characteristics which are consistent with a firmground interpetation: sharp walls, contrasting burrow fill with encasing sediment, and an overprint of a new ichnofauna on the softground ichnofauna. The significance of the firmground characteristics must now be considered.

Two constraints on firmground development were observed: 1) the nature of the host substrate, and 2) the position along topographic features developed at the top of the Raven River Member. Burrows are found best developed in mudstones, indicating that the organisms present preferred a semicohesive mud substrate. The predominantly sharp nature of the unconformity indicates that in most places the sandstone was lithified prior to erosion and the mudstone at least semicohesive. Rare occurences of disturbed contacts may indicate local areas of uncohesive sediments at the time of erosion.

The second control on burrow distribution is the position of the burrows in relation to the unconformity topography. Firmgrounds tend to be preferentially developed on the northeast sides of the topographic ridges defined by Leggitt (1987). In relation to the paleoshoreline in Cardium time, northeast is basinwards (Leggitt, 1987). In Pembina, the most consistent firmground development has been found to exist in the northwest part of the field and towards Carrot Creek. More rarely, burrows are found in the southern part of the field, however these occurrences seem to be quite isolated (S. Leggitt, p. comm., 1987).

SUMMARY - A MODEL FOR FIRMGROUND DEVELOPMENT

No cases of totally nonmarine firmground have been recorded in the modern or in the rock record (refer to table 1). Thus, if Pembina was subaerially exposed, it must have been exposed to further erosion in a marine or marginal marine setting prior to conglomerate deposition. Topography at the base of the conglomerate is not suggestive of incised drainage patterns, and the amount of topography is too great to equate to offshore erosional processes, such as those observed in Recent settings (Bergman and Walker, 1987).

Ichnofossils examined in this study were consistently infilled with pebbly mudstone. There is little evidence that emplacement was active, i.e. carried out by the tracemaker. The ichnology of strata above the contact (bioturbated pebbly mudstones) suggests that the environment was lower shoreface to offshore. Recent work in the Carrot Creek area has topography developing in the Cardium Formation by rapid regression allowing shoreface development in shelfal sediments (Bergman and Walker, 1987). Leggitt (1987) extended these ideas to the Pembina oilfield and found that the topographic ridges present in Pembina were also formed by shoreface erosion, although the field was emergent during maximum lowstand of sealevel. Periods of tilting due to tectonic pulses followed by slow readjustment allow the preservation of shoreface ridges. Abrupt episodic downwarps formed the Northern Bevel and Poplar Valley, with more steady transgression forming Buck Valley (Leggitt, 1987). Direct evidence for subaerial exposure of the E_5 contact is lacking, although indirect diagenetic evidence from siderite occurrences is present (Bartlett, 1987). Bergman (1987 in Leggitt, 1987) interprets the conglomerate at Carrot Creek as a gravelly shoreface deposit banked against a major bevel surface (Bergman and Walker 1987). The conglomerate and sandstone characteristics in the Carrot Creek area appear to be consistent with shoreface emplacement, as described by Bourgeious and Leithold (1984) and Nemec and Steel (1984). Transgression blanketed the

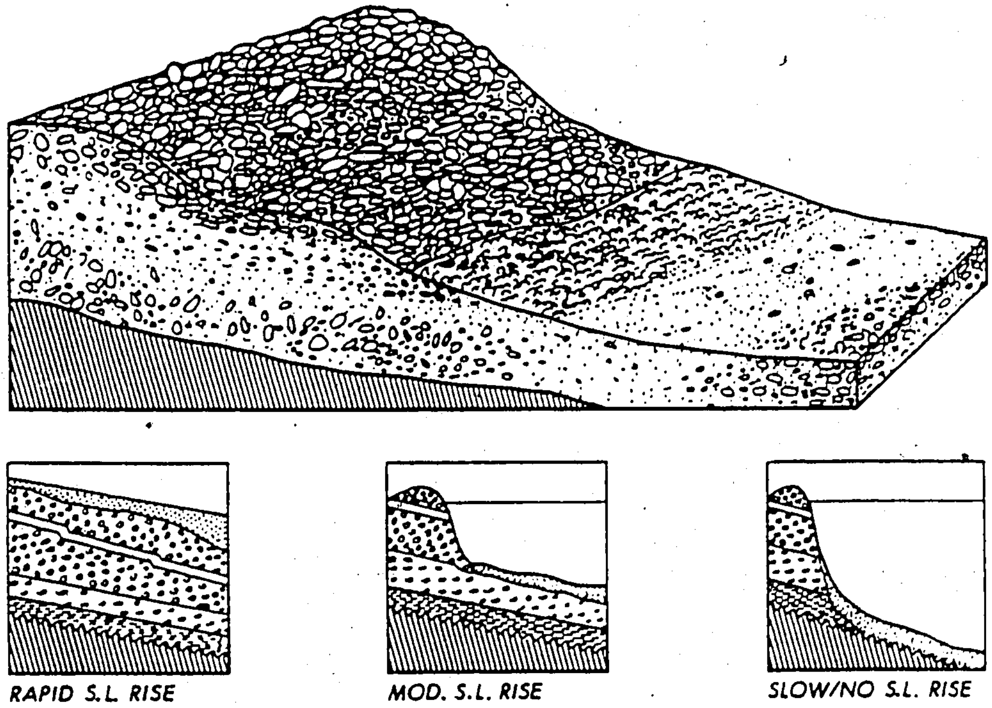


Figure 13. Preservation potential of gravelly shoreface deposits (top block) during varying rates of sea level rise. (modified from Nemec and Steele, 1984; Davis and Clifton, 1987)

shoreface gravels with offshore deposits of mudstone. During lowstand of sealevel, incised rivers transported conglomerate alongshore against the bevel and into erosional hollows, protecting them from further erosion. Conglomerate size trends and the morphology of the conglomerate pods in Pembina suggest that the river source supplying conglomerate to the shoreface may have been to the south, with thick pods of conglomerate concentrated at or near river mouths (Leggitt, 1987).

Ichnofossils at the base of the conglomerate in the northwest part of Pembina are associated with the Carrot Creek bevel and the area just south of this, extending north to the Northern bevel. Initially, a shoreface was eroded into the shelfal sediments in the area of the Northern bevel and eventually infilled with conglomeratic nearshore deposits (Leggitt, 1987). At this time, it is possible that all of Pembina south of this shoreface was subaerially exposed. With transgression and readjustment of the basin, a new shoreface was emplaced in the Poplar Valley area. At this time, a population of firmground burrowers inhabited offshore to marinal marine regions of this new shoreface. The burrows are developed during periods of active erosion due to wave energy in a storm dominated coastline. In the high energy coastal setting, nutrients are abundantly available. As a gravel shoreface developed, destructive processes reworked former shoreface deposits and pebbles were transported offshore as a transgressive lag to passively fill abandoned burrows. The absence of ichnofossils in areas with thick conglomerate may be explained by 1) high energy conditions limiting biotic activity or 2) scour associated with gravel emplacements removing existing burrows. Limited development of firmgrounds in southern Pembina may be linked to more southerly shoreline positions. Ichnofossils in the Carrot Creek area are associated with the offshore bumps and hollows of Bergman and Walker (1987). Wave erosion offshore enabled opportunistic organisms to exploit newly exposed unoccupied substrates (Vossler and Pemberton, 1987; Vossler and Pemberton in press).

The absence of paleosols and an incised drainage network on the unconformity surface present difficulties that must be overcome by this model. While the presence of paleosols or rooted zones is definitive evidence for subaerial exposure, the absence of paleosols does not negate exposure. In Holocene offshore sediments which are known to have been subaerially exposed prior to drowning, paleosols or rooted zones are almost never preserved (Nummedal and Swift, 1987). In a high energy, storm dominated coastline, destructive processes prevail and paralic (shoreward of the shoreface) deposits tend to be reworked and moved offshore. In this process, a ravinement surface is formed, which may alter and or remove drainage network patterns (Nummedal and Swift, 1987: Demarest and Kraft, 1987). This is especially true if sea level rise following lowstand is gradual rather than rapid (Davis and Clifton, 1987), as a stepwise progression of the shoreface across Pembina would suggest. Since all documented outcrop and subsurface occurrences of the Cardium Formation are storm-dominated, a destructive coastline setting is probable. With the tectonically active Cordillera to the west, sea levels in the foreland basin of the Western Interior may have been greatly influenced by tecotnic events. Thrusting events in the mountains and foothills caused subsidence in the basin (Kauffman, 1984; Beaumont, 1981), and if sedimentation cannot keep pace with this subsidence, then sea level rises (Demarest and Kraft, 1987). Sea level drops (such as the one responsible for bevel surfaces in the Pembina area) may be eustatically or tectonically controlled.

In another occurrence of the E_5 surface at Seebe, Alberta(R.G. Walker, personal communication, 1987), pebble filled *Rhizocorallium* were observed by one of the authors (S. Vossler). This, along with south Pembina burrowed horizons, suggests that the E_5 surface is commonly burrowed, with firmground development perhaps much more extensive than shown in this study. Another unconformity horizon (E4) of the Cardium

Formation in the Edson oilfield has been observed by the senior author to have pebble filled *Thalassinoides* below the contact. Firmgrounds are found locally along the unconformities of the Cardium Formation, wherever conditions are beneficial to colonists.

EROSION SURFACES AND STRATIGRAPHY IN THE CARDIUM FORMATION

The combined work of Bergman (1986); Bergman and Walker (1987); Plint *et al.*, 1986; 1987, Leggitt, 1987; and Bartlett, 1987, in addition to the evidence presented herein show that the E5 surface is probably ubiquitously erosional throughout northwestern Alberta in the subsurface. This fact has been used by Plint *et al.* (1987) to defend a subsurface stratigraphy based on seven erosion surfaces (pebbly log markers and the bases of thick conglomerates), and overlying transgression surfaces. Some criticisms of this stratigraphy were presented by Hayes and Smith (1987), and Rine *et al.* (1987). While all of the log markers used by Plint *et al.* may represent widesread erosion, more study of the other horizons must be done before conclusions can be drawn regarding their genesis. However, acceptance of the stratigraphy of Plint *et al.*(1986; 1987) should be dependent of the usefulness and correlatability of the members rather than on the wholesale acceptance of the proposed interpretation of the log markers. The event stratigraphy of the Cardium that Plint *et al.* proposed is convenient, and appears to express true stratigraphic relationships in the Pembina - Carrot Creek area.

THE IMPORTANCE OF UNCONFORMITY RECOGNITION

The use of unconformity bounded packages has become a common practise among stratigraphers (Salvador, 1987), and has been the basis of an 'event stratigraphy' for the Cardium (Plint *et al.*, 1986). An 'event stratigraphy' approach as used by Plint et al. (1986; 1987) attempts to delineate stratigraphic units based on genetically related packages of strata, and correlates these based on the occurrence of widespread bounding unconformities. This idea is closely related to those of Mitchum et al. (1977), who defined new terms for interpretation of stratigraphic sequences found on the passive margin-Atlantic coastline, where unconformity-bounded packages can be recognised in seismic profilesand correlated to world-wide fluctuations in sea level (Vail *et al.*, 1977). The basic unit of this sequence stratigraphy approac is the depositional sequence: unconformity (or their correlative conformity) bounded packages of genetically related beds (Mitchum *et al.*, 1977). In the work of Vail *et al.*(1977)and Mitchum *et al.*(1977), the unconformity surface representing maximum lowstand of sea level (or the absence of beds from that time) is the base of a depositional sequence seperate from that which contains the underlying Raven River Member. The top of the Carrot Creek Member is above the top the conglomerate, where the deepest water deposition takes place (here when laminated mudstones pass into monotonously bedded black mudstones)(Mitchum et al., 1977). The latest sea level curves reveal at least three major sea level fluctuations in Turonian time (Haq et al., 1987). The correlation of this sequence to sequence stratigraphy of the passive margins is problematic however, since deposition an dealevel in the foreland basin would be influenced to a large extent by local tectonics (Kauffman, 1984), which overprint and obscure true eustatic changes in sea level.

Several workers have studied the large scale correlation of unconformities and unconformity bounded packages in the Western Interior of North America. Sloss (1984) identified three classes of unconformity on a regional and interegional scale: 1) the result of uplift and erosion accompanying deformation in orogenic belts, 2) unconformity as the result of submarine erosion, 3) intercratonic unconformities related to the cessation of deposition, the initiation of erosion and the reestablishment of depositional regimes responsible for regional and interegional unconformities. All three of these unconformity types are of a larger scale than the essentially intraformational unconformities of the Cardium. In work of a similar vein to that of Sloss, Wiemer (1984) documented a period of large -scale erosion of shelfal strata during a period of sealevel lowstand (90 m.y. before present). During lowstand erosion by wave energy or by subaerial processes may have removed shelfal of slope deposits (Wiemer, 1984).

The evidence for significant fluctuations of sea level leading to erosion is strong for various Turonian age rocks. Equivalent strata to the Cardium Formation - Frontier Formation in Wyoming, and the Tocito-Gallup Formationsin New Mexico - have been subject to alternating periods of deposition and erosion leading to unconformities (Merewether *et al.*, 1979; Tillman, 1985).

The occurrence of widespread intraformational unconformities appear to be significant in many Cretaceous deposits in the interion of North America. Unconformities with firmground development have been observed in the Viking Formation, and in the Clearwater Formation, both in the Alberta basin (S. G. Pemberton, personal communication). The Greenhorn and Fairport Formations in the western United States have erosional valleys cutting into shelf deposits which are later filled by chert pebbles and sandstone (Wiemer, 1984). Plint and Walker (1987) documented a shoreface incised into shelfal deposits of the Bad Heart Formation of Alberta (Santonian) during a lowstand of sea level.

CONCLUSIONS

From the evidence presented here it can be concluded that the base of the conglomerate in Pembina represents a significant unconformity, which is the base of a depositional sequence. A burrowed firmground horizon exists at the base of the conglomerate in the northern part of the Pembina oilfield and organisms which burrowed at this horizon preferred semicohesive mud substrates. The absence or limited occurrence of burrows elsewhere in Pembina may be due to a greater depth of burial and thus consolidation of sediments. These ichnofossils were filled with pebbles and mud-sized sediment during a trangression which reworked pre-existing shoreface deposits and eventually blanketed the unconformity surface and conglomerate with relatively deep-water mudstones.

In order to identify depositional sequences in areas other than the passive margin, sedimentological and faunal evidence may be necessary where seismic data is inconclusive. In the Cardium Formation, the occurrence of a firmground horizon confirms that sea level fluctuations which delineate a depositional sequence have occurred and provides insight into the mechanisms of erosion at the bounding unconformity surface. The recognition of other firmgrounds in the ancient record can be beneficial in pinpointing lithologically subtle unconformities which can be significant in regional stratigraphy.

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CHAPTER FIVE: *SKOLITHOS* IN THE UPPER CRETACEOUS CARDIUM FORMATION: AN ICHNOFOSSIL EXAMPLE OF OPPORTUNISTIC ECOLOGY

INTRODUCTION

In recent ecological studies of benthic organisms, equilibrium or K-selected species have been distinguished from opportunistic or r-selected species. Opportunistic species can respond rapidly to an open or unexploited niche and are characterized by (1) a lack of equilibrium population size, (2) a density-independent mortality, (3) the ability to increase abundance rapidly, (4) a relatively poor competitive ability, (5) high dispersal ability, and (6) having a high proportion of resources devoted to reproduction (Grassle and Grassle 1974). Opportunistic organisms display an r-strategy in population dynamics, emphasizing rapid growth rate (r), while equilibrium species adopt a K-strategy based on the carrying capacity of the environment (K) (Boesch andRosenberg 1981). Short generation span is the most important mechanism for increasing population size in an r-strategy, therefore lifespans of opportunistic species are shorter, and sexual maturation is reached earlier (Rees *et al.* 1977). Broad environmental tolerances and generalised feeding habits facilitate rapid colonization of open niches (Pianka 1970).

Relatively little work has been done to relate these population strategies to the ichnofossil record. Ekdale (1985) summarized a number of possible examples resulting from (1) turbidite deposition (i.e. Seilacher, 1962; Ksiazkiewicz, 1977; Kern, 1980); (2) salinity variations (i.e. Miller and Johnson, 1981; (3) oxygen deficiencies (i.e. Brenne and Seilacher, 1978; Bromle and Ekdale, 1984); and (4) storm deposition (i.e. Howard, 1972; Ward and Lewis ,1975). In all of these cases some sort of physical and/or chemical stress was applied

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to the benthic population. It will be demonstrated in this paper that the ichnogenus *Skolithos* in examples from the subsurface Cardium Formation from the Pembina and Carrot Creek oilfields of western Alberta provides an excellent example of opportunistic strategy preserved in the rock record.

STUDY AREA

Seventy-eight cores from the Cardium Formation (Turonian) were examined from the Pembina -Carrot Creek oilfield of west-central Alberta, whose location is shown in Fig. 3. All core are stored at the Energy and Resources Conservation Board Core Research Centre in Calgary, Alberta. The Cardium Formation, along with the underlying Wapiabi Formation and overlying Blackstone Formation, comprises the Upper Cretaceous Alberta Group.

SEDIMENTOLOGY OF THE CARDIUM FORMATION IN THE PEMBINA AND CARROT CREEK OILFIELDS

In the core examined, the Cardium Formation consists of one or two coarsen- upward sequences of mudstone and fine-grained sandstone, unconformably overlain by conglomerate or mudstone. These sequences are comprised of heavily bioturbated mudstone,with the percentage of fine sand particles increasing upward, grading into thin interbeds of fine grained sandstone and mudstone followed by thick bedded fine grained sandstone. In the most recently proposed subsurface stratigraphy, strata below the unconformity represent the Raven River Member, and strata above the unconformity represents the Carrot Creek Member (Plint *et al.*, 1986).

The mudstones of the Raven River Member coarsen upward from less than 5% fine sand to approximately 50% fine sand. We suggest that the mudstones represent interbedded sandstone and mudstone that have been homogenized by biogenic reworking.

This lithology has been shown to indicate periodic influxes of coarser sediment, followed by periods of slow, steady sedimentation (Ekdale *et al.,* 1984). Thin, sharp-based sandstone beds occur sparsely within the mudstone, increase in thickness and abundance toward the top, forming a gradational transition to interbedded sandstone and mudstone. These uppermost beds are composed of fine grained sand size particles having disk-shaped shale clasts concentrated near the base. Physical sedimentary structures present include plane parallel to gently inclined laminations. Occasionally, the tops of the sandstone beds display wave ripple laminations. Similar structures and sequences in core have been interpreted as hummocky cross stratification (Tillman and Martinsen , 1985). Sandstone beds show a subtle fining upward trend and may grade into the overlying mudstone through biogenic mixing. While in most of the thin sandstones only physical structures were observed, in some examples ichnofossils were present. In most instances one ichnogenus dominates the unit (*Skolithos*, and more rarely *Ophiomorpha*).

The general sequence of the coarsening upward cycles is one of sandstone beds increasing in thickness and abundance upwards into the sandstone beds, which may represent amalgamated storm units.

SEDIMENTOLOGICAL CHARACTERISTICS

Storm events constitute an important mechanism for the transport of sand onto the shelf (Swift and Niedorada , 1985). In the ancient record they tend to be unusual compared to surrounding lithologies, and in shelfal deposits are usually characterised either by hummocky cross-stratification or sharp-based siltstone beds (Winn *et al.,* 1983; Walker, 1985; Brenchley, 1985; Pedersen , 1985; Hurst and Pickerill , 1986). In addition, storm activity may generate turbidity flows depositing Bouma sequences (Walker, 1985; Nelson, 1982). Initially, storms tend to resuspend bottom sediments, scouring the seafloor, and carrying debris landward (Hayes, 1967). This can have a winnowing effect on the seafloor, resulting in basal lag deposits (Kreisa , 1981), or the condensation of beds and firmground/hardground development in stratigraphic sequences (Walker, 1985).

Following the initial shoreward currents, sand is carried onto the shelf by geostrophic currents moving parallel to isobaths, by storm-surge ebb currents, or by storm generated turbidity currents (Walker, 1985). Thin parallel laminated sandstone units are common; and are interpreted as intermediate depth storm deposits . Preserved storm layers observed on the modern Puerto Rican mud-dominated inner shelf are thirty to fifty centimetres and may have been up to one metre thick when first deposited, with ten to twenty centimetre beds on the outer shelf (Brackett and Bush, 1986). The sand layers deposited by storms, unless very thick, will be completely mixed with the surrounding shelf muds by biogenic activity, providing conditions favour an active infauna (Kreisa, 1981). The nine centimetre graded blanket of sand spread by hurricane Cindy, observed by Hayes (1967), was unrecognisable twenty years later (Dott , 1983).

Hummocky cross-stratification, which is common in all outcrop occurrences of the Cardium Formation, is difficult to recognise in core, but may occur throughout the section. It is a bedform associated with storm deposition of sand, is characterised by sharp-based beds of fine sand to coarse silt sized particles with low angle truncations and terminations and low angle laminae which are convex or concave upwards; there is an upward growth of hummocks from parallel laminations (Duke, 1985). An ideal hummocky cross-stratification sequence consists of: (1) a sharp base overlain by a coarse lag deposit which may be graded, (2) plane parallel lamination, (3) hummocky cross-stratification, (4) flat lamination, often undulatory, (5) ripple lamination, and 6) mudstone which is generally bioturbated. Hummocky cross-stratification occurs in 10-200 centimetre beds interbedded with mudstone or in amalgamated beds with thin shale partings which may be bioturbated.

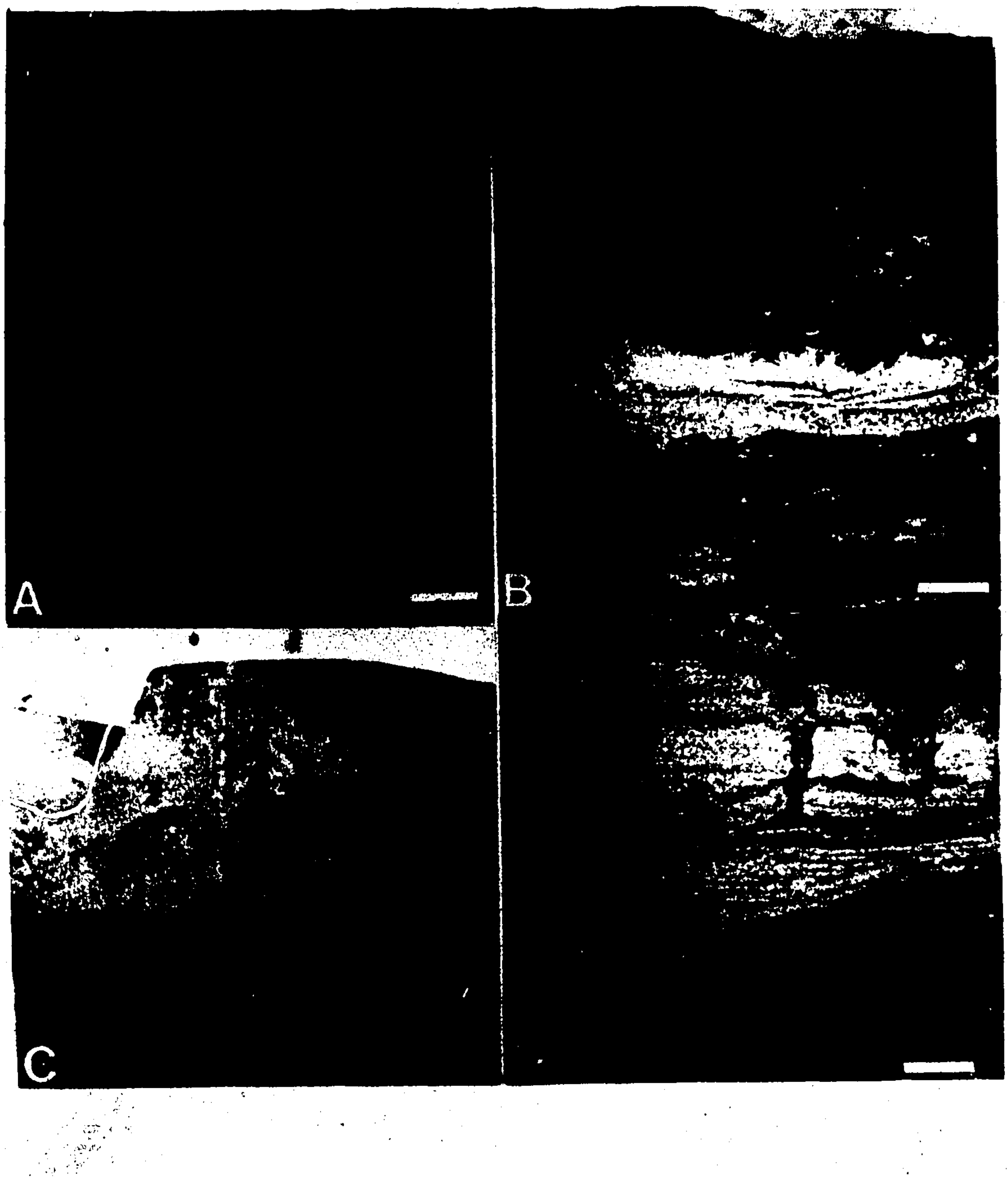
FAIRWEATHER CONDITIONS AND THE STABLE COMMUNITY

The ichnotaxa found in the Raven River Member mudstones represents the activitiy of the stable community. Ichnogenera present include: *Helminthopsis, Planolites, Terebellina, Teichichnus, Zoophycos, Rhizocorallium, Asterosoma, Rosselia, Palaeophycus, Chondrites, Thalassinoides,* and *Skolithos*. The typical appearance of the equilibrium ichnofossils is shown in Plate 7. These ichnogenera represent diverse ethological categories, showing a dominated by deposit-feeders, but no single ichnogenus is numerically dominant. The density and diversity of ichnofossils in an ichnological assemblage cannot be directly linked to the density and diversity of organisms present (Rhoads, 1975); ie. one organism can be responsible for several ichnofossils, while several different organisms can leave identical ichnofossils. Pervasive bioturbation, coupled with the high diversity and low abundance of individual ichnogenera, indicates a complex and stable community in an area, having a slow and steady sedimentation rate (Frey and Pemberton , 1985). Only unusually thick storm sands will be preserved in a shelfal setting with high bioturbation rates due to abundant infaunal organisms.

OPPORTUNISTIC COLONISATION

In most instances, the ichnocoenose of the storm-derived sandstone units contain only a single ichnogenus, *Skolithos*, although in rare instances *Ophiomorpha* or *Rosselia* were also noted. In these units *Skolithos* are characteristically small (diameter of 2-3 mm), vertical, has thin (approximately 0.1 mm) clay linings, is straight, and never branches. Two or three burrows may occur in the width of a core (10 cm in diameter), suggesting that locally densities can be quite high. Storm sandstones with *Skolithos* are shown in Plate 7. Additional *Skolithos*-rich horizons were also found associated with the mudstones. These

Plate 7. Core photographs. All core are stored in the Energy and Resources Conservation Board Core Research Centre in Calgary, Alberta. Numbers in brackets are well locations, using the Dominion Survey of Canada. A. *Zoophycos* in mudstone of the Cardium Formation. Notice the thin sandstone bed (indicated by arrow; centre of photo) which has been partially destroyed by bioturbation.(LSD 6-31-53-13W5M) B. Sharp based sandstone bed in homogenised mudstones. Numerous *Skolithos* come down from a sandstone bed(indicated by arrow) where the core is broken. Approximately one centimetre is missing where the picture is cut.(14-10-53-13W5M) C. Amalgamated sharp based sandstone beds with two*Skolithos* horizons. (9-3-52-11W5M) D. Amalgamated sandstone beds with several thinly-lined *Skolithos* coming down from the top of the uppermost sandstone.(6-31-53-13W5M). Scale bar is equal to one centimetre in all photographs.


A
B
C

organism, with possible tracemakers including polychaetes or phoronids (Pemberton and Frey, 1984b). In ecological studies of recent environments, polychaetes are consistently the most common opportunistic organism group (McCall and Tevesz, 1983). Fauchald and Jumars, (1979) indicated that suspension-feeding has been documented, in some form or another, in 13 families of polychaetes. Where gregarious behaviour is indicated by the high densities of *Skolithos*, a mucous net or tentacular crown is the most likely feeding implement (Barnes 1980; Pemberton and Frey, 1984b).

EFFECTS OF STORM ACTIVITY ON THE EQUILIBRIUM POPULATION

Storm activity disrupts bottom fauna, resulting in mass stranding and the transportation of organisms to other environments (Hayes, 1967; Rees *et al.*, 1981;Dobbs and Vozarik, 1983). Sand or mud deposition following storms can bury the stable community present on the shelf (Brongersma-Sanders, 1957; McKnight, 1969). Organisms may survive this by burrowing out to their preferred dwelling depth, leaving perturbations in the sedimentary structures (Schäfer, 1972). If the depth of burial is too great, benthic and infaunal organisms suffocate, which can result in the well-preserved death assemblages found in many ancient tempestites (Schäfer 1972; Brett *et al.*, 1986;).

The escape potential of bivalves following sudden burial was examined in detail by Krantz (1974). While infaunal bivalves have the ability to escape when the burying medium was the same as their natural substrate, exotic sediment posed a greater problem. Organisms appear to be adapted to burrow in a limited range of substrates, and have great difficulty moving in and manipulating foreign sediment. The infauna of the shelf muds comprising the Cardium Formation may similarily have had difficulty burrowing up through storm sand blankets. The combination of seafloor scouring and sand deposition via storm processes could completely depopulate the normally quiet, stable, shelf area.

RECOLONISATION FOLLOWING DISRUPTION

burrows displayed similar dimensions but were unlined. This may indicate an obscured wall lining and a concealed bed junction or perhaps such horizons are indicative of semi-cohesive substrates exhumed via storm scour and recolonised with unlined *Skolithos*.

Ethologically, *Skolithos* represents the dwelling burrow of a suspension-feeding organism, with possible tracemakers including polychaetes or phoronids (Pemberton and Frey, 1984b). In ecological studies of recent environments, polychaetes are consistently the most common opportunistic organism group (McCall and Tevesz, 1983). Fauchald and Jumars, (1979) indicated that suspension-feeding has been documented, in some form or another, in 13 families of polychaetes. Where gregarious behaviour is indicated by the high densities of *Skolithos*, a mucous net or tentacular crown is the most likely feeding implement (Barnes 1980; Pemberton and Frey, 1984b).

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RECOLONISATION FOLLOWING DISRUPTION

Recolonisation of modern benthic communities following physical or chemical disruption has been documented by numerous workers (Grassle and Grassle, 1974; Rhoads *et al.*, 1977; Simon and Dauer, 1977; Grassle , 1977; Rees *et al.*, 1977; Santos and Simon, 1980; Sanders *et al.* , 1980; Thistle , 1981; Bonsdorff, 1983; Whitlatch and Zajac, 1985). The results of these studies are summarized in Table 4.

Recruitment into depopulated regions is initiated by either adult or larval forms (Santos and Simo, 1980), thus the composition of the larval pool helps determine the species available for recolonisation (Jackson, 1983). Zajac (1986) noted that adults of opportunistic species become sexually active after a physical disturbance or after seasonal depopulation, allowing a very rapid increase in the size of the larval pool. The larvae of small invertebrate opportunists are generally brooded, allowing them to settle almost immediately after release from the parent. Gray (1974) noted that opportunistic organisms can have both planktonic and benthic larvae, thereby giving them very flexible recruitment abilities. Thorsen (1966) found that larvae preferentially selected suitable substrates for settling, as opposed to an indiscriminant "larval rain upon the seafloor". Polychaete larvae appear to be able to postpone metamorphosis until a suitable substrate is available (Thorsen , 1966). Once settled, the mature larva must metamorphose quickly to adult form.

In addition to substrate texture, the chemistry of the water may affect the success of larval settlement. In a study of the opportunistic polychaete *Capitella*, settling was found to

TABLE 4: MODERN EXAMPLES OF RECOLONIZATION FOLLOWING DEFAUNATION

Author	Environment	Stress	First Colonist	Second Colonist	Others
Grassle & Grassle 1974	estuary-nearshore	oilspill	1st month: *Capitella capitata*	8 months: *Polydora ligni*	*Microphthalmus aberrans, Syllides verilli, Streblospio benedicti*
Dauer & Simon 1976	intertidal	red tide	1st month: *Polydora ligni*	2-3 months: *Eteone heteropoda, Nereis succinea*	year 2: *Capitata ambiseta, Minuspio cirrifera, Trovisia* sp.
Pearson & Rosenberg 1978	microtidal fiord	pollution	3 yrs:*Capitella capitata*	*Scolepsis fulignosa*	
Grassle 1977	deep sea 1760m	experimental defaunation	2 months: *Priapulis atlantsi*	28 months: *Capitella* sp.	
McCall 1977	embayment	experimental defaunation	10 days: *Streblospio benedicti, Capitella capitata, Ampelisca abdita*	50 days: *Nucula proxima*	
Rees *et al.* 1977	shallow marine	storms			mobile predators with short life cycles
Rhoads *et al.* 1978	estuary	dredging	10 days: *Streblospio benedicti*	29-50 days: *Capitella capitata* *Ampelisca abdita*	50 days: *Nucula annulata* 86 days: *Tellina agilis* 175 days: *Nephthys incisa*
Sanders *et al.* 1980	marine-estuary	oil spill	1st 11 months: *Capitella*	2nd year *Mediomastus*	
Desbryers *et al.*, 1980 in Thistle 1981	offshore 2160 m.	experimental defaunation	6 months: *Prionspio* sp. *Ophryaboche puerilis*		
Bonsdorff 1983	shallow brackish	dredging	*Nereis diversicolor, Corophium volutator Macoma balthica*		

be triggered by the presence of sulphides in the water column (Cuomo, 1985). Storm currents that scour the sea floor may increase the sulphide content by uncovering sediments in which decay of organic matter has already occurred. Also, mass-death following a physical disturbance will increase the sulphide content.

Santos and Simon, (1980) found that adult recruitment from surrounding areas can be appreciable in some circumstances. Adult recruitment may be facilitated by the transport of adults by storm currents, and subsequent relocation. Recolonisation following storm disruption in a nearshore environment, sheltered from current energy was studied by Rees *et al.,* (1977). It was found that following large storms, mass-stranding and redistribution of numerous species occurred, with adult organisms and the larval forms being displaced to open ocean areas, mediating rapid recolonisation.

Studies of recolonisation rates of stable and unstable (fluctuating salinity, sedimentation and temperature) modern environments shows that organisms in stable environments are more severely affected by physiological stress. Species present in unpredictable environments, such as estuaries, usually have broad environmental tolerances and can recover from disturbances quickly (Jernelöv and Rosenberg, 1976). Relatively stable deep sea environments can take longer than two years to recover completely, while relatively unstable estuarine environments may recover in approximately 11 months (Dauer and Simon, 1976; Grassle, 1977). Marginal marine organisms are subject to relatively high physiological stress on a continual basis, and thus the resident population is likely to exhibit some degree of r-selected strategy (Ekdale, 1985). For example, Rhoads *et al.,* (1985) found very small shaft dwelling organisms that were probably opportunistic comprising the normal community in nearshore areas with a rapid rate of sedimentation.

Recolonisation, if it progresses without disturbance, will follow a trend to more complex and deep burrowing behvior as shown in Fig. 14.

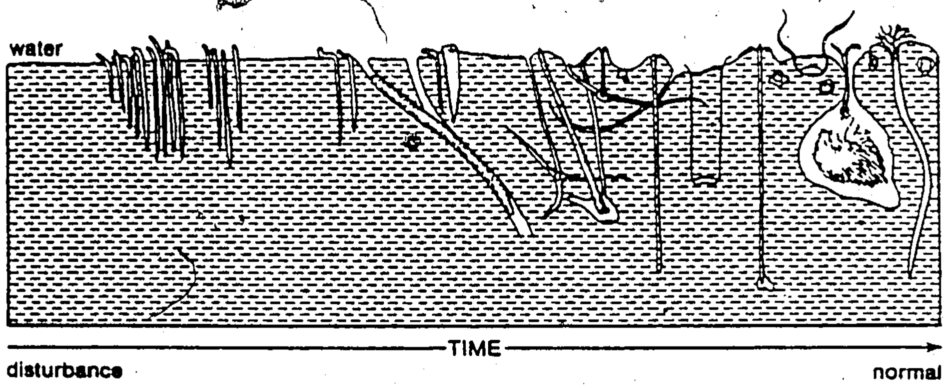

Figure 14. The reestablishment of benthic community following disruption. (modified from Rhoads *et al.*, 1978)

LIFESTYLES OF OPPORTUNISTIC ORGANISMS

Opportunistic organisms display tolerance to a wide range of physiologically stressful conditions. Thus the lifestyles of opportunistic polychaetes in disturbed systems can be somewhat variable (Grassle and Grassle, 1974). In the examples reviewed in Table 1, opportunistic colonists were errant-burrowing or tube-dwelling deposit-feeders. Suspension-feeding at the sediment/water interface differs very little from (and may be gradational with) surface deposit-feeding, where a suspended load of nutrients is found close to the bottom. Organisms use similar apparati for both strategies. However, Cadée (1984), noted that opportunistic organisms have a great capability to vary their feeding habits depending on food available in the habitat. Thus, if suspension-feeding is the most viable strategy, opportunistic organisms would utilize it.

Some commonly identified modern opportunistic polychaete genera include: *Capitella, Mediomastus, Nereis, Polydora, Streblosia,* and *Hobsonia* (Grassle and Grassle, 1974; Sanders *et al.,* 1980; Santos and Simon , 1980; Whitlatch and Zajac, 1985). While most of these are errant-burrowing or tubiculous surface deposit-feeders, *Polydora* is a suspension-feeder, *Nereis* and *Capitella* can suspension-feed or deposit-feed, and some species of *Capitella* are also predators (Barnes, 1980; Thayer, 1983; Cadeé, 1984; Whitlatch and Zajac, 1985). In recolonized dump areas, the earliest colonist was found to be the deep-burrowing polychaete *Nephthys incisa,* followed by tube dwelling deposit-feeding polychaetes, and finally bivalves (Rhoads *et al.,* 1977). Unlike components of the stable community, pioneering species have generally been found to have a negligible effect on sediment properties below the sediment/water interface (Rhoads *et al.* , 1978). Many polychaetes line their burrows with a thin mucus coating to enhance stability (Barr[illegible], 1[illegible]80). This form represents the most simple, primitive, and quickly constructed of all b[illegible]

Washed-in sediment eventually forms a thin clay wall, and the burrows will be preserved as shaped burrowing textures (Schäfer, 1972). Tube dwelling organisms which suspension feed have been found to dominate early recolonisation of marine areas (Rhoads, 1975).

Opportunistic colonists tend to live in dense clusters (Rhoads *et al.,* 1978). Gregarious settling is used to inhibit competitors from settling (Whitlatch and Zajac, 1985). Among opportunistic species, individuals tend to settle near conspecifics, indicating gregarious settling behaviour is based on the presence of others rather than on the availability of preferred substrate. Since these organisms tend to brood their larvae, they can settle immediately upon release from the adult, allowing rapid crowding of a given space. The initial colonists thus preempt space, inhibiting the settlement of other species.

Palaeontological evidence

The characteristics of an opportunistic body fossil assemblage in the rock record (as reiterated by Pemberton and Frey, 1984a) are: (1) limited areal distribution (Waage, 1968), (2) occurring in a continous, thin, isochronous horizon (Waage, 1968), (3) abundant in several, otherwise distinct faunal assemblages (Levinton, 1970), (4) having great abundance in a facies with which it is not generally associated (Levinton, 1970), (5) numerical domination of one species within the fossil assembage (Levinton , 1970).

Waage (1968) noted possible opportunistic body fossil assemblages in the Maestrichtian Fox Hills Sandstone of South Dakota. Assemblage zones attributed to mass mortality were found bounded by sparsely populated to barren units. The sudden abundance of fauna was attributed to a slight decrease in stress allowing a settlement in the newly opened niche.

Rollins *et al.,* (1979) documented a faunal succession within a community which contained an opportunistic brachiopod-gastropod assemblage; stress was applied by shallow marine conditions associated with early transgressions. Epifaunal suspension-feeders

TABLE 5: COMPARATIVE ICHNOLOGY OF STORM VERSUS FAIRWEATHER DEPOSITS

Age	Formation	Ichnofossils (fairweather)	Ichnofossils (storm)	Reference
Mid-Upper Ordovician	Martinsburg Formation	none given	*Planolites* , fugichnia	Kreisa 1981
Lower Silurian	Ross Brook Formation	mottling, *Chondrites*, *Helminthopsis*	*Skolithos*, *Palaeophycus*	Hurst & Pickerill 1986
Lower Silurian	Hughley Formation	*Scolicia*, *Walcottia*, *Rusophycus*, *Cruziana*	*Diplocraterion*, *Skolithos*, *Chondrites*, *Palaeophycus*	Benton & Gray 1981
Middle Silurian	Thorold Formation	*Arthrophycus*, *Chondrites*, *Cruziana*, *Daedalus*, *Diplichnites*, *Dolopichnus*, *Lingulichnus*, *Lobichnus*, *Monomorphicnus*, *Palaeophycus*, *Planolites*, *Polycylindrichnus*, *Rusophycus*, *Teichichnus*	*Skolithos*, *Diplocraterion*, *Arenicolites*	Pemberton & Risk 1982
Lower Carbon-iiferous	Courceyan andArundian Formations	none given	*Zoophycos*, *Planolites*, *Rhizocorallium*,fugichnia	Wu 1982
Lower Cretaceous	Choshi Group	none given	*Planolites montanus*, *Nankaites*, steeply inclined *Palaeophycus*	Katsura *et al.* 1984
Upper Cretaceous	Frontier Formation	*Asterosoma*, *Teichichnus*	*Ophiomorpha*	Winn *et al.* 1983
Upper Cretaceous	Shannon Sandstone	*Asterosoma*, *Skolithos*, gastropod trails, *Teichichnus*, "donut burrows" (possibly*Terebellina*), *Thalassinoides*	*Skolithos*	Tillman & Martinsen 1985
Upper Cretaceous	Cardium Formation	*Chondrites*, *Planolites*, *Cochlichnus*, *Phoebichnus*, *Meunsteria*, *Rhizocorallium*, *Zoophycos*, *Thalassinoides*, *Cylindrichnus*, *Rosselia*, *Gyrochorte*, *Planolites*	*Skolithos*, *Diplocraterion*,	Pemberton & Frey 1984a *Palaeophycus*

Table 5 (continued)

Age	Formation	Ichnofossils (fairweather)	Ichnofossils (storm)	Reference
Upper Cretaceous	Star Point Formation	*Scolicia, Palaeophycus herberti, Palaeophycus tubularis, Cylindrichnus concentricnus, Thalassinoides suevicus, Teichichnus rectus, Planolites beverlyensis, Planolites montanus, Ancorichnus capronus, Ophiomorpha annulata*	*Ophiomorpha nodosa, Skolithos linearis*	Howard & Frey 1984
Upper Cretaceous	Cape Sebastian Sandstone	*Ophiomorpha, Planolites, Scolicia, Sabellarites, Thalassinoides, Macaronichnus segregatis*	*Ophiomorpha*	Hunter & Clifton 1982
Upper Cretaceous	Cape Sebastian Sandstone	*Ophiomorpha, Planolites, Scolicia, Sabellarites, Thalassinoides*	fugichnia, *Scolicia, Ophiomorpha*	Bourgeois 1980
Mid Tertiary	Arno	*Imbrichnus, Scolicia, Planolites*	*Ophiomorpha*	Ward & Lewis 1975
Oligocene	Magazine Pt. Formation	*Thalassinoides,*	*Ophiomorpha*	Lewis 1980

dominate the assemblage. Later, an equilibrium population appears to develop, but with the transgressive nature of the deposit there is some doubt that interspecific competition (necessary for a true ecological succession) was responsible for the biotic change.

Diminuitive bivalves with paedomorphic traits were interpreted as opportunistic species in an area of low oxygen concentrations demonstrating that evolutionary characteristics can provide evidence for life strategies (Snyder and Bretsky, 1971). The relationship between paedomorphosis and ecology was examined by Gould (1977). Gould's theory stated that accelerated sexual maturation is associated with r-selecting paedomorphs, whereas retarded somatic development characterizes K-selecting paedomorphsis, and is supported by recent models on ecological causation of heterochrony (McKinney , 1986). The example cited by Snyder and Bretsky, (1971) is suggestive of accelerated sexual development, diagnosed by reduced size of descendants relative to their ancestors (McNamara, 1986).

In another body fossil example, an opportunistic fauna of trilobites was documented by Brezenski (1986) in strata which were interpreted as representing reduced oxygen conditions.

Ichnological evidence

The activities of soft-bodied infauna which have low preservational potential as body fossils represent a significant component of any biological succession (McCall and Tevesz, 1983). Nevertheless, the ichnofossil record can preserve the activities of the soft bodied, benthic organisms (Ekdale *et al.*, 1984). Thus, the ichnofossil record may be the best place to find evidence of opportunistic colonists in an ecological succession. As noted earlier, some of the difficulties in recognizing part of an ecological succession in the rock record are: (1) fossiliferous strata tend to encompass long temporal ranges in comparison with the scale of Recent faunal successions; and (2) strata tend to include obvious environmental changes that are beyond the control of the resident organisms, i.e. interspecific interaction is not the primary reason for the change in biota (McCall and Tevesz, 1983).

Pemberton and Frey (1984a) studied an opportunistic assemblage of ichnofossils from the Cardium Formation at Seebe, Alberta. In this example, the resident ichnocoenose was disrupted by rapid storm sedimentation. Storm-current emplaced beds were invaded by an opportunistic fauna which in turn was replaced by a stable community when conditions were stable once again. Opportunistic lifestyles were represented in the Cardium Formation by *Skolithos*, *Diplocraterion* and *Ophiomorpha*. The ichnofossils show a change from a diverse, predominantly deposit-feeding community to a less diverse, but locally abundant suspension feeding community. Table 5 records other possible examples.

DISCUSSION

The thin, *Skolithos* -rich storm beds of the Raven River Member in the Cardium Formation seem to fulfill the requirements of an opportunist ichnocoenose. The beds appear to be isochronous, each representing a single storm event. As a result, the scale of the units is at the level necessary for the recognition of opportunistic behaviour. It seems likely that the ichnofauna preserved in the beds is influenced most strongly by the physical depopulation and subsequent recolonisation of sediment in a shelfal setting. The abundance of one form, and the exclusion of other ichnogenera, is also consistent with an opportunistic interpretation.

The small size of *Skolithos* associated with storm sands of the Raven River Member provides further corroboration for an interpretation of opportunistic recolonisation, since opportunistic species are generally smaller than equilibrium species. While the size of burrows cannot be directly correlated with the size of the trace-making organism, in the case of a simple dwelling-shaft it is likely that the burrow is only slightly larger than the inhabitant.

The very thin clay lining found in the burrows suggests a simple and quickly constructed domicile in somewhat uncohesive substrates. As previously stated, the ichnofossil

Skolithos has been interpreted as the dwelling burrow of a suspension-feeding organism. Suspension-feeding and surface deposit-feeding are common feeding strategies for early colonists in Recent sediments and vertical burrowing is a prevalent adaptation to stressful environments (Thayer, 1983). Based on the studies of modern sediments reviewed earlier in this paper, polychaetes seem to be the most likely opportunistic suspension-feeders responsible for the abundant *Skolithos* .

The high density of *Skolithos* observed probably represents the gregarious nature of the colonizing organisms. Vertical burrows tend to relate the life position of the inhabitant, especially when the inhabitant is essentially immobile (Pemberton and Frey, 1984b) and each shaft represents the activity of an individual organism (Thayer, 1983). It is likely, given the synchronous nature of each storm bed, that the shafts are approximately the same age.

Recruitment into this open niche could have been enhanced by substrate type and possibly by water chemistry. Suspension feeding organisms may prefer sandy substrates such as the storm sand blanket (Ekdale *et al.*, 1984). Methanic diagenesis must have taken place at shallow depth owing to decay of organic material in the Raven River Member as evidenced by the presence of primary siderite nodules (Baird *et al.*, 1986). Thus storm activity would increase the concentration of sulphide ions in the water column, thus acting as a trigger for larval settlement. In the case of *Skolithos* from thin storm generated sandstone beds, reestablishment of a normal shelf community may have been gradual and due primarily to interspecific competition. This is strongly suggested by *Skolithos* - rich beds that have tops mixed into overylying mudstones by later bioturbation.

The presence of an opportunistic *Skolithos* horizon in a sequence can be useful in interpreting the microdynamics of a sedimentological or ecololgical system. Each bed containing the horizon can probably be attributed to the work of a single storm, and evaluation of the time needed to reestablish a normal benthic community can give some idea of sedimentation rates. The occurrence of some seemingly homogeneous thin sandstones with several *Skolithos* -rich horizons is an indication of amalgamated storm beds, since each burrowed zone represents a single storm.

Skolithos -rich horizons in the mudstones of the Raven River Member may indicate concealed bed junction preservation, where discrete storm sands have been obliterated by bioturbation (Ekdale *et al.,* 1984). Another possibility is that storm currents have eroded away overlying muds to form a thin 'firmground' which was exposed to the activities of burrowing suspension-feeding organisms similar to the opportunistic organisms of the storm emplaced sandstone beds (Aigner, 1982). Firmground burrows tend to have very sharp walls, indicating the cohesive nature of the substrate.

CONCLUSIONS

While evolutionary palaeontology may provide insights into life strategies adopted by organisms, the ichnofossil record may enhance and increase our knowledge of opportunistic behaviour in the past. Ichnofossils preserve the activities of otherwise unfossilised soft-bodied fauna, which are observed in the Recent to be the predominant opportunistic biota.

Thin, storm emplaced sandstones found in a quiet shelfal sequence, such as those present in the Cardium Formation, provide ideal examples of opportunistic recolonisation. The abundant *Skolithos* in the sandstones is one such example. The recognition of an opportunistic fauna may help to elucidate the microdynamics of sedimentary deposits by identifying small discontinuties in mudstone sequences, and by revealing amalgamated storm deposits.

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CONCLUSIONS

How then have these four papers enhanced understanding of ichnology in general and the ichnology of the Cardium Formation in particular? First, a relatively comprehensive knowledge of the appearance of common ichnogenera present in shelfal facies in core has been gained. The use of core is ubiquitous already in the petroleum industry, and will undoubtedly grow in other areas of research in the future. Academic workers can no longer ignore the vast bed of knowledge about formations in the subsurface which core represent. Understanding of ichnofossils (and as well sedimentary structures) will grow only if published drawings, photo's and descriptions of them are widely available.

Beyond the mere description of forms, the ichnogenera identified from the Cardium help to elucidate several palaeoecological situations. A comprehensive model of bioturbation fabric and ichnofossils associated with offshore deposits is attempted. The full verticla section afforded by core enables a fairly detailed look at distal-proximal storm-generated deposits in a prograding sequence. Complex ichnofossil relationships between pre and post- storm ichnogenera and between shallow and deep burrowing forms can be discerned. Form this example, the complex interplay of assorted environmental parameters which control ichnofossil distribution can interact to complicate the across the board application of ichnofacies modeles. In a storm dominated shelfal environment the frequency and intensity of storm disturbance is the most important control on the occurrences of ichnofossils. A hasty examination of the ichnogenera present, using a bathymetric approach to ichnofossil assemblages would tend to invoke unecessarily complex flux of sea levels to explain ichnogenera occurrence.

One of the most controversial aspects of the Cardium Formation is the presence of multiple conglomerate/pebble horizons. One of these conglomerate beds is present in the Pembina area, overlying multiple coarsening upward sequences of mudstone and sandstone. The basal surface of this conglomerate has been interpreted as an erosion surface, which is a depositional sequence boundary. Firmground ichrofossisl are found locally at this erosion surface, indicating firm but unlithified sediments at the time of erosion. The indentification of firmgrounds aids in the recognition of sea level fluctuations which are significant, but engender only subtle lithologic changes. Firmgrounds have proven to be beneficial in recognising sequence boundaries which are important in the tectonically active foreland basin of the Western Interior Seaway. In the case of the Cardium Formation, the identification of a firmground ichnofossiol suite confirms preexisting ideas about sequence boundaries in the formations and provides additional information which allows refinement of ideas on sea level fluctuations which dominate Cardium depositon. Far reaching implications for further exploration of sequence stratigraphy are foreseen with future recognition of firmground ichnofacies. Perhaps future work in this field can be founded on this initial documentaion of sequence stratigraphy and associated ichnofossils.

One of the most important palaeoecological findings of this thesis is the documentation of an opportunistic occurrence of *Skolithos* in storm-generated sandstone beds. This is an excellent example of opportunistic suspension-feeding organisms exploiting a niche which is suddenly available and vacant. As well as illustrating an important example of a rarely documented situation, this study of *Skolithos* provides a format for evaluating preexisting models and examples of opportunistic behavior in the fossil record.

This study of the ichnology of the Cardium Formation has been of benefit by exploring a new aspect of an importnat hydrocarbon producer in subsurface and by putting forth ideas which are more widely applicable. While the Cardium Formation is important locally, at the time of this writing, the problems of shelfal ichnology are more widespread and will be pondered well into the future. So, while assisting in the interpretation of the somewhat problematic Cardium Formation, this work has also been of more far reaching interest.

APPENDIX I: CONTACTS LOGGED

Well Location	**Contact type**		
	bioturbated	sharp	obscured
14-32-50-10W5M		x	
1-32-50-10W5M	x		
16-20-50-10W5M		x	
6-26-50-10W5M	x		
2-9-51-10W5M	x		
6-9-51-10W5M	x		
12-24-50-12W5M		x	
14-11-51-11W5M	x		
10-1-50-12W5M			x
6-3-51-10W5M	x		
6-7-50-9W5M	x		
6-13-50-10W5M	x		
6-8-51-9W5M	x		
6-8-50-9W5M	x		
13-34-50-9W5M	x		
8-36-49-8W5M			x
8-4-50-8W5M		x	
14-30-49-7W5M			x
14-30-49-10W5M			x
6-12-50-9W5M		x	
14-34-49-11W5M			x
9-7-51-9W5M			x
16-34-49-11W5M		x	
14-35-49-11W5M		x	

6-10-50-10W5M		x	
4-30-49-7W5M	x		
14-35-49-8W5M			x
16-24-49-8W5M			x
6-25-50-10W5M			x
16-21-50-10W5M	x		
6-7-50-10W5M		x	
8-7-50-10W5M		x	
6-19-50-10W5M			x
16-6-50-10W5M			x
12-20-50-10W5M	x		
14-9-50-10W5M		x	
6-12-50-10W5M	x		
16-5-51-10W5M			x
14-5-51-10W5M			x
16-34-50-10W5M	x		
4-29-51-11W5M		x	
12-8-51-10W5M		x	
2-17-51-10W5M		x	
14-35-50-11W5M	x		
4-31-51-10W5M			x
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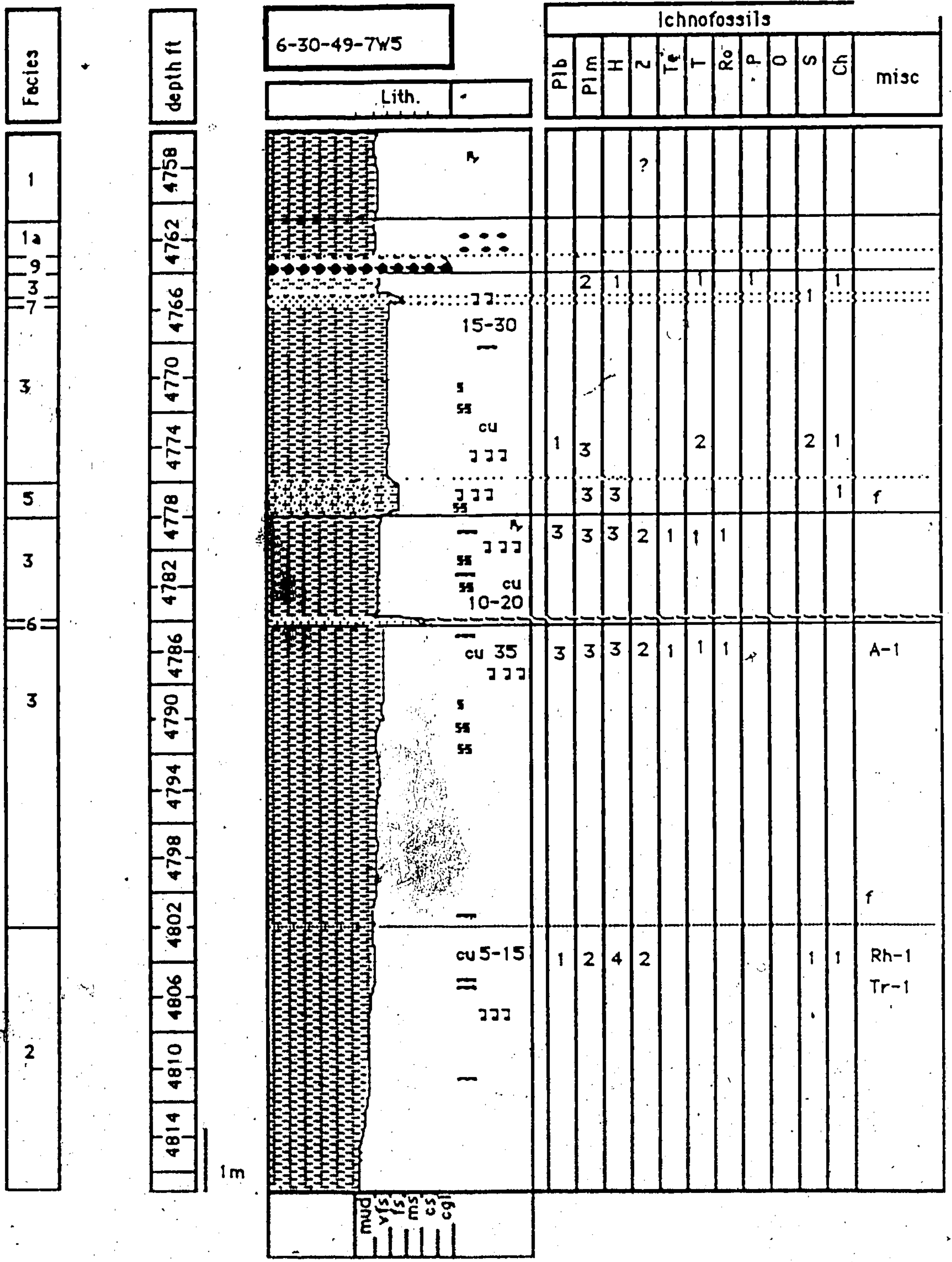
APPENDIX II: CORE LOGS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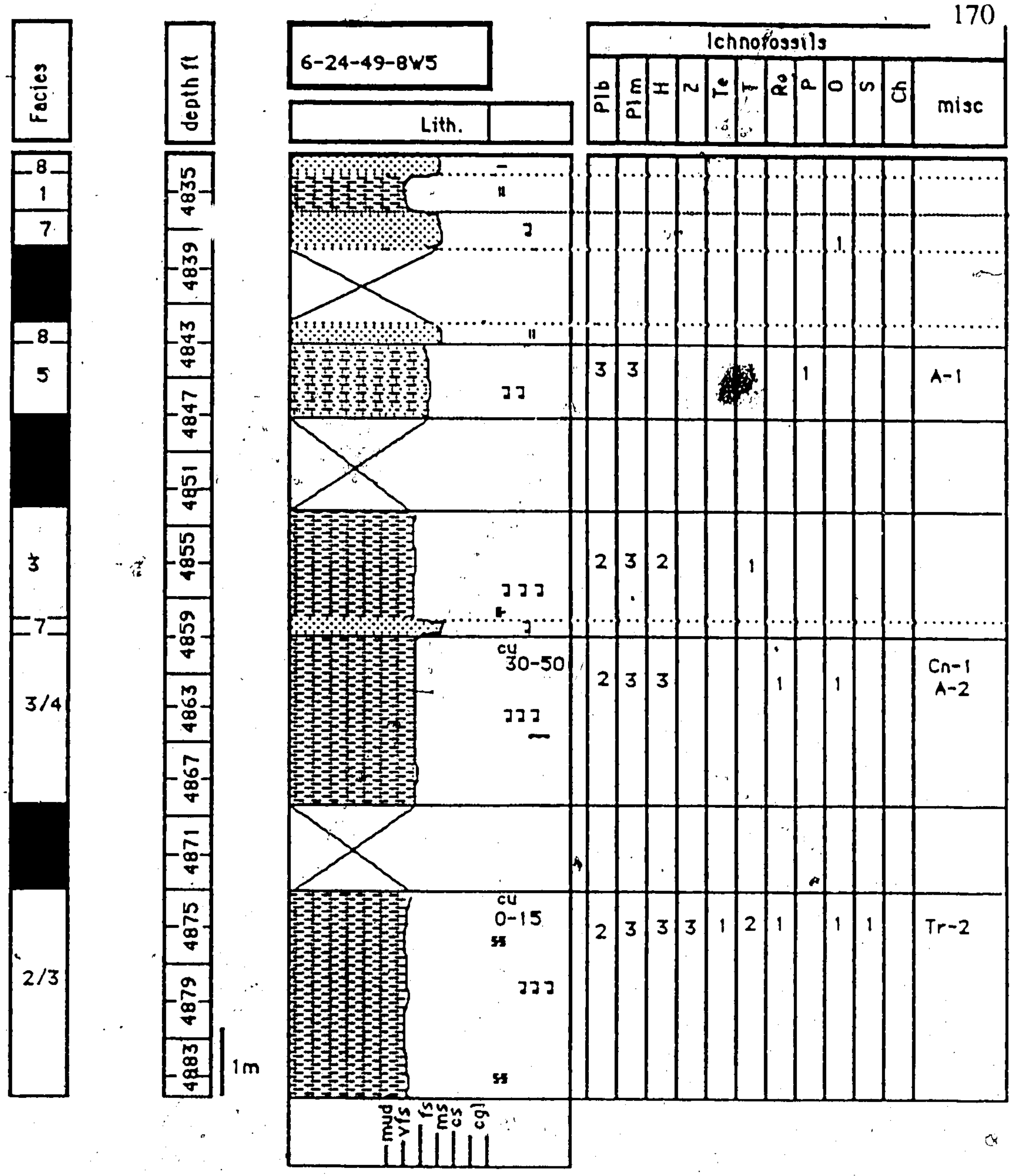
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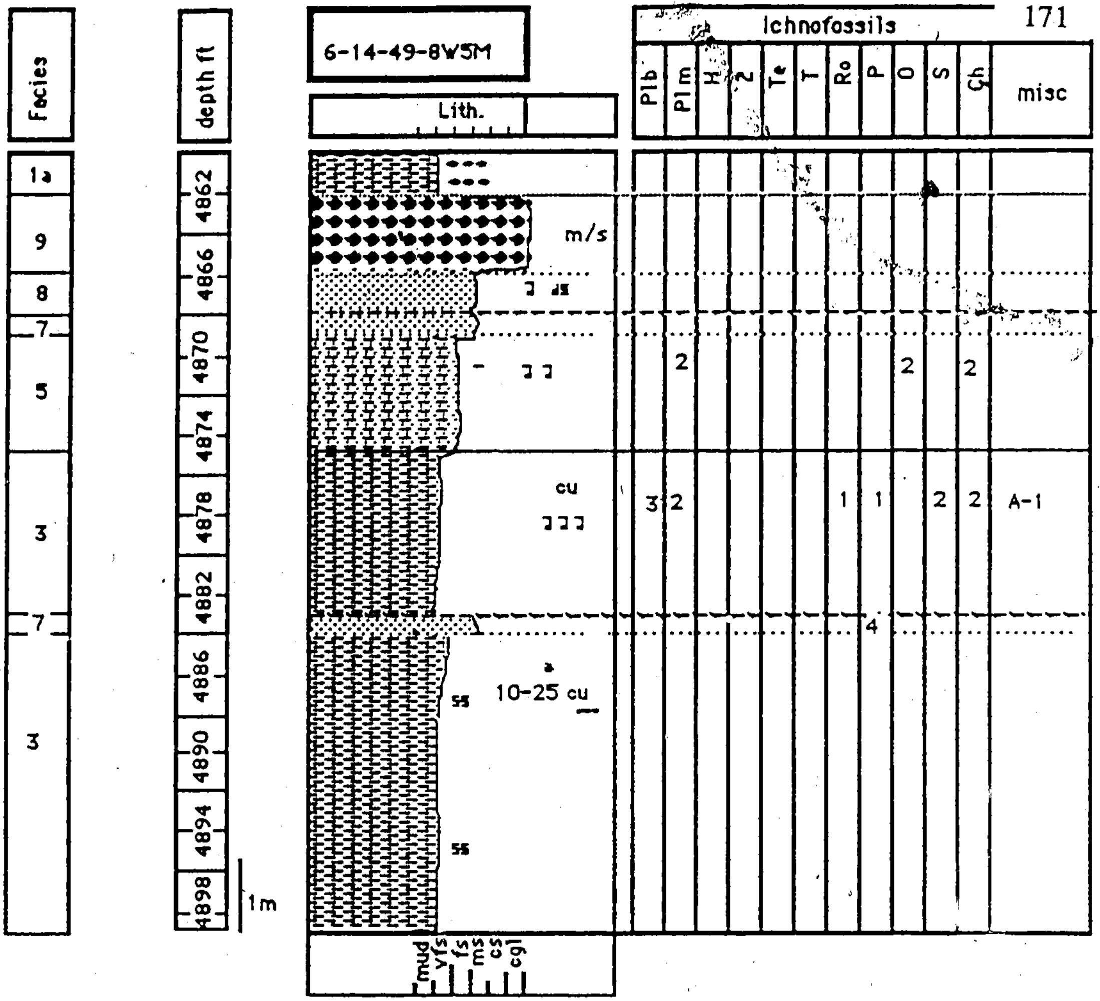

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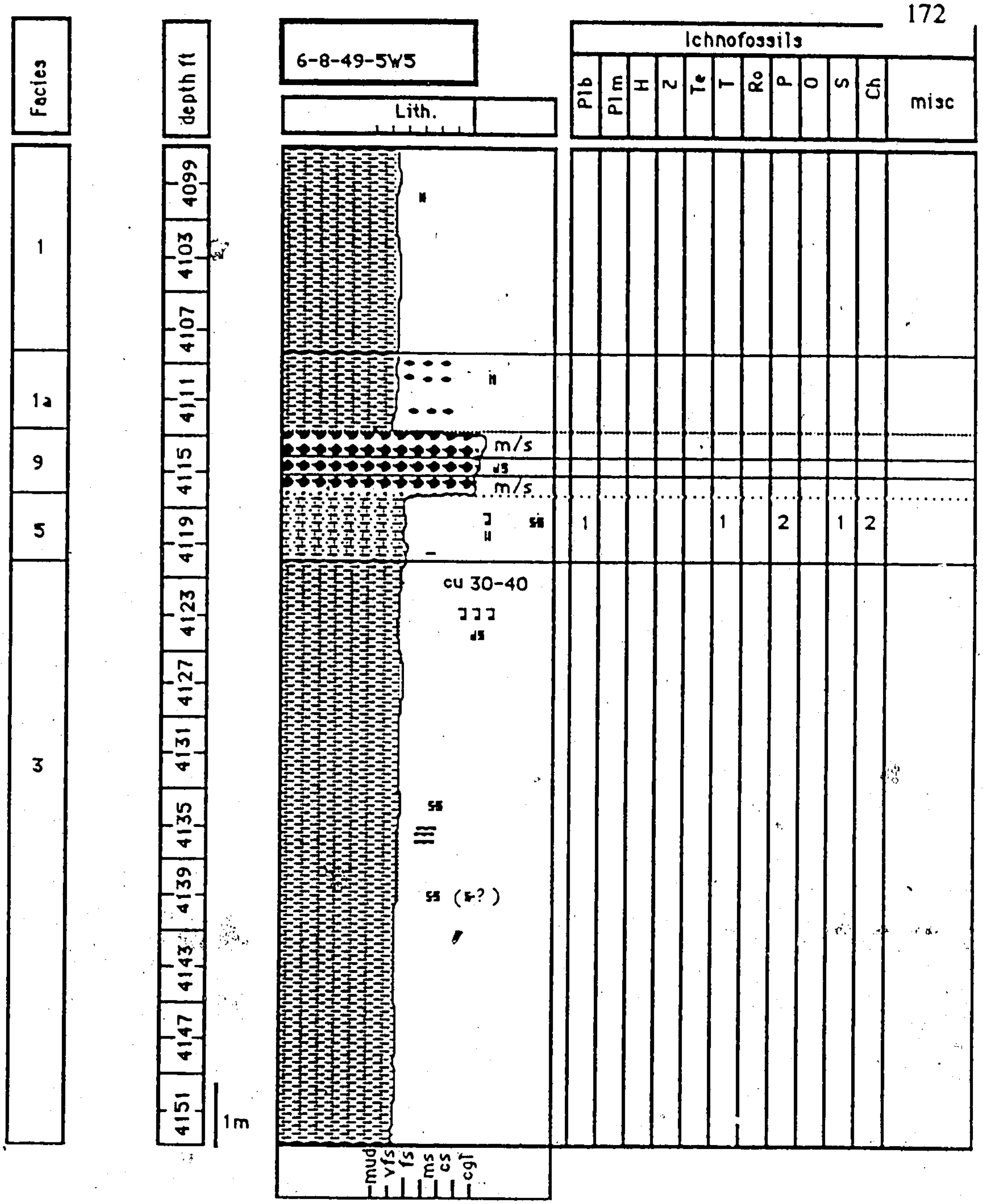
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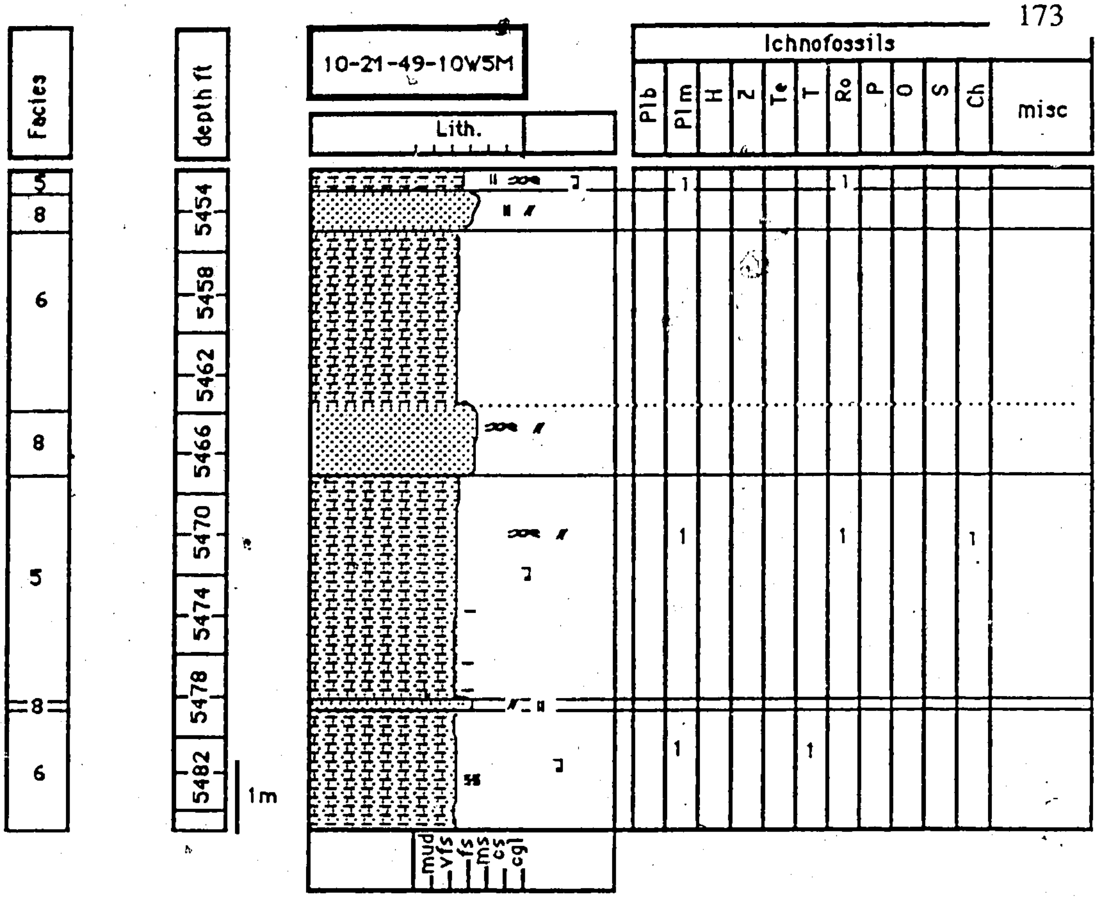
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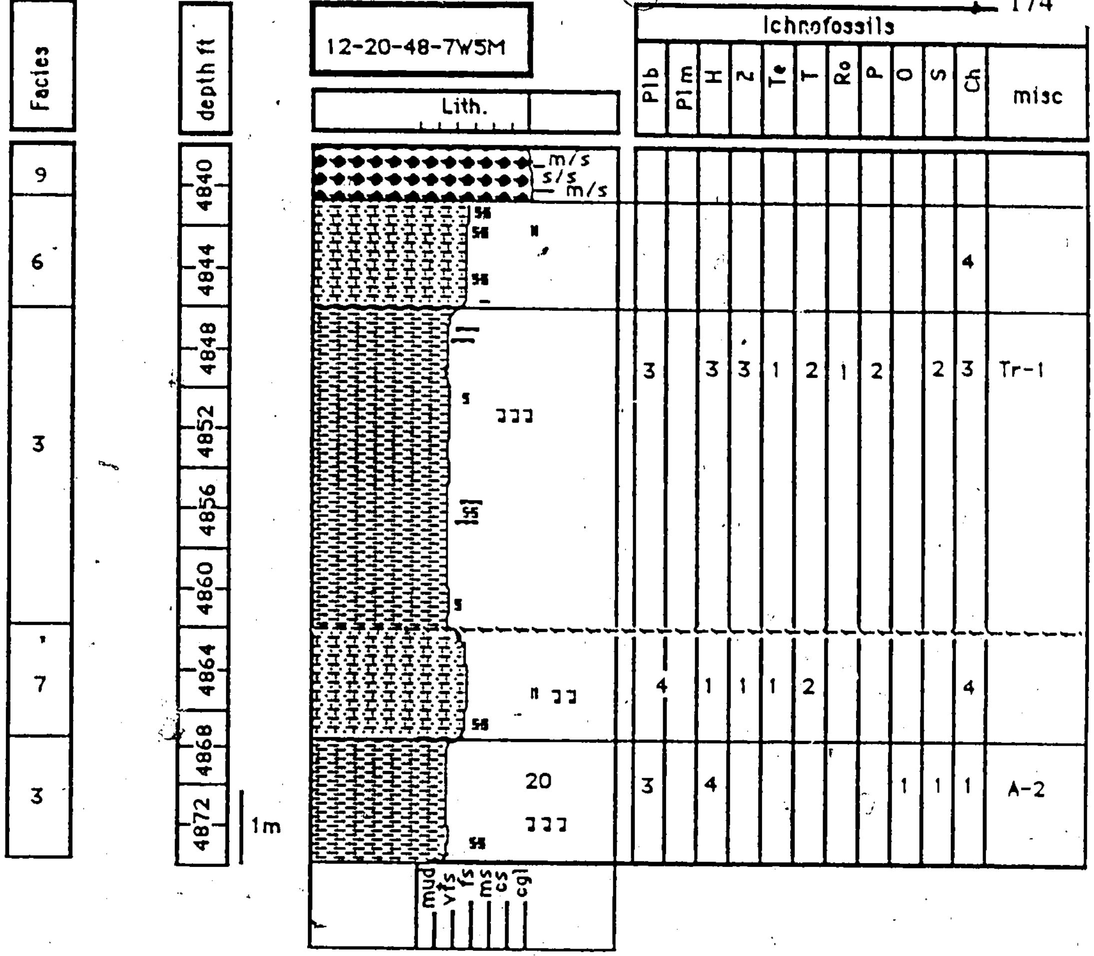
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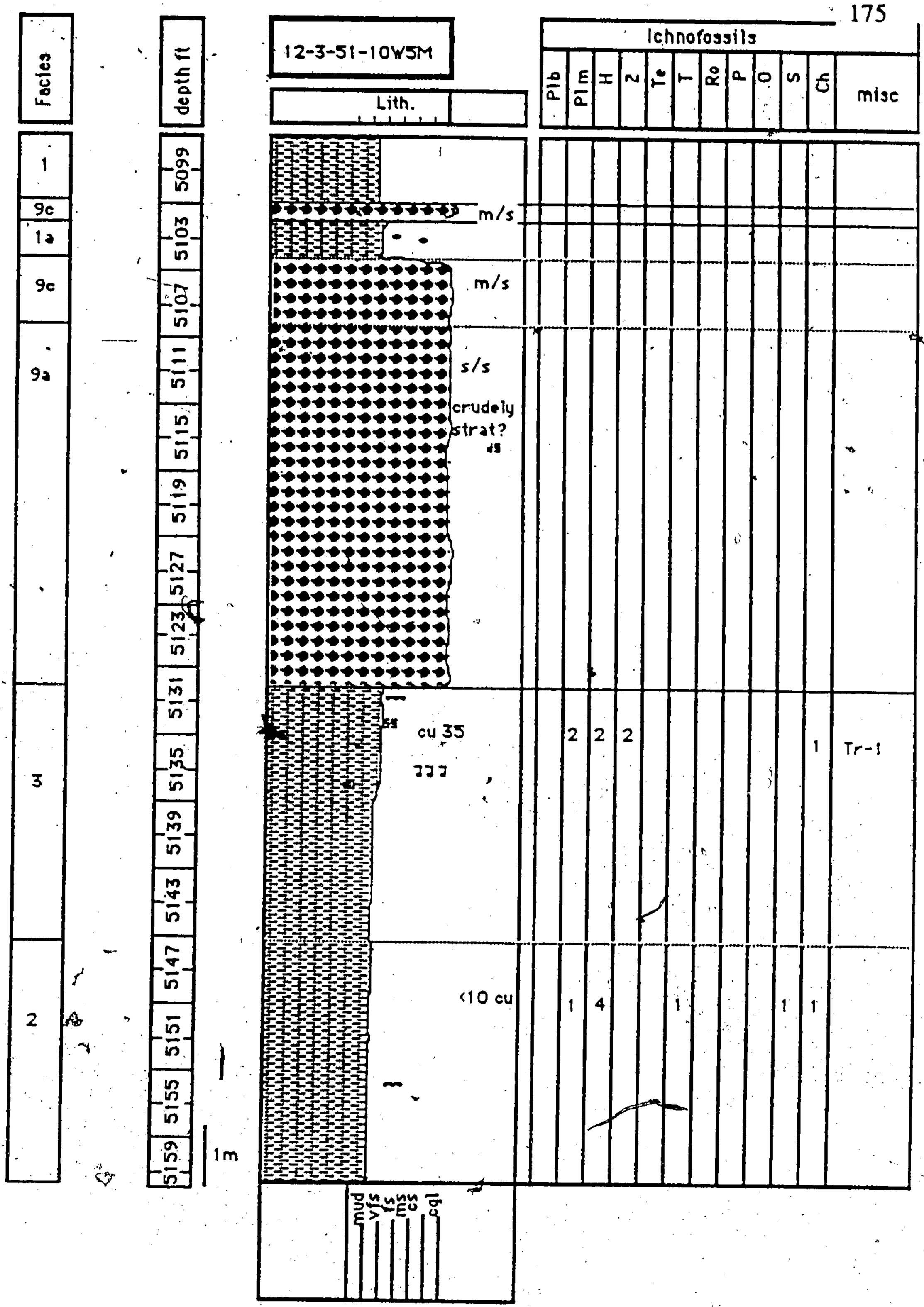
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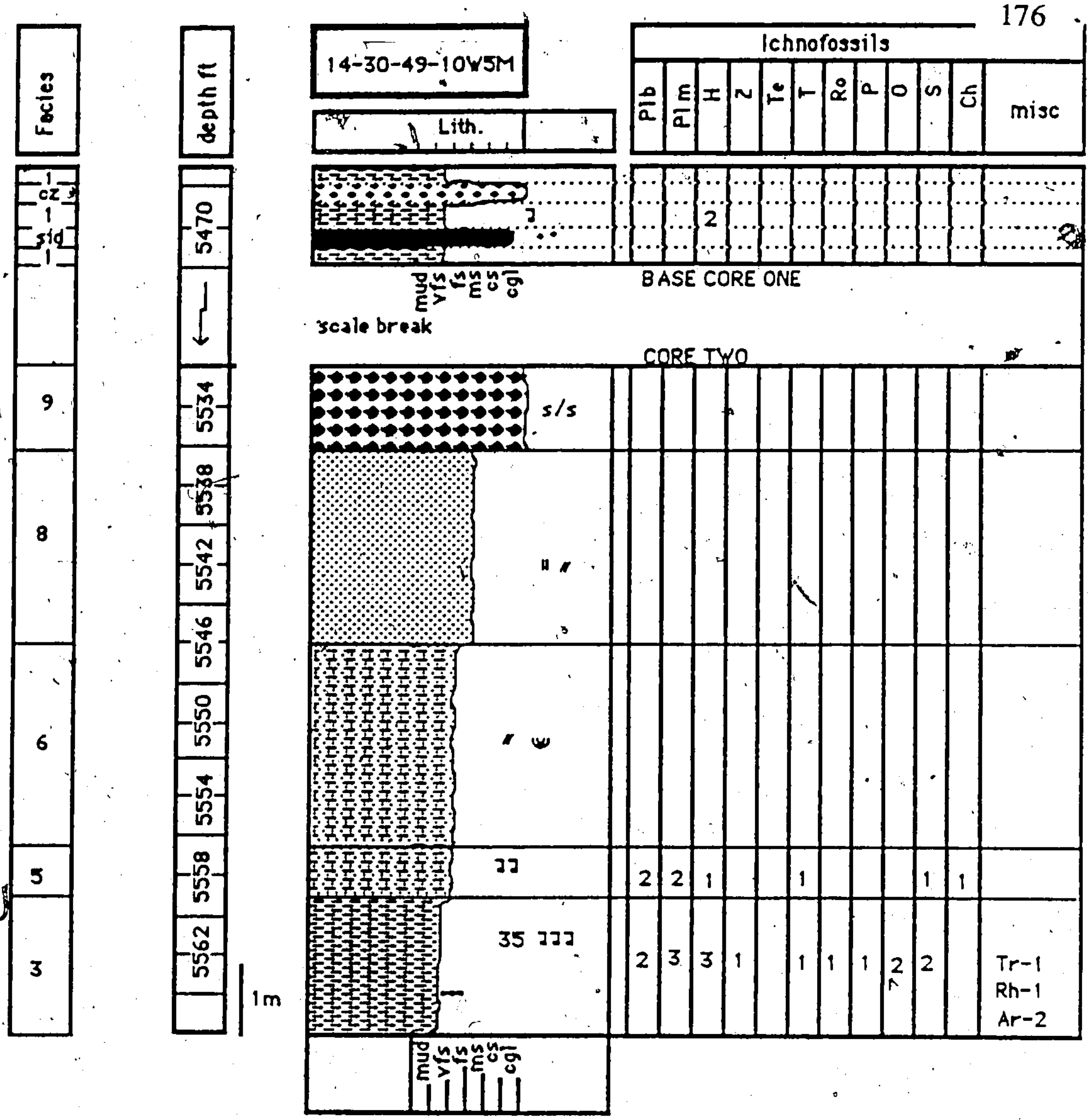
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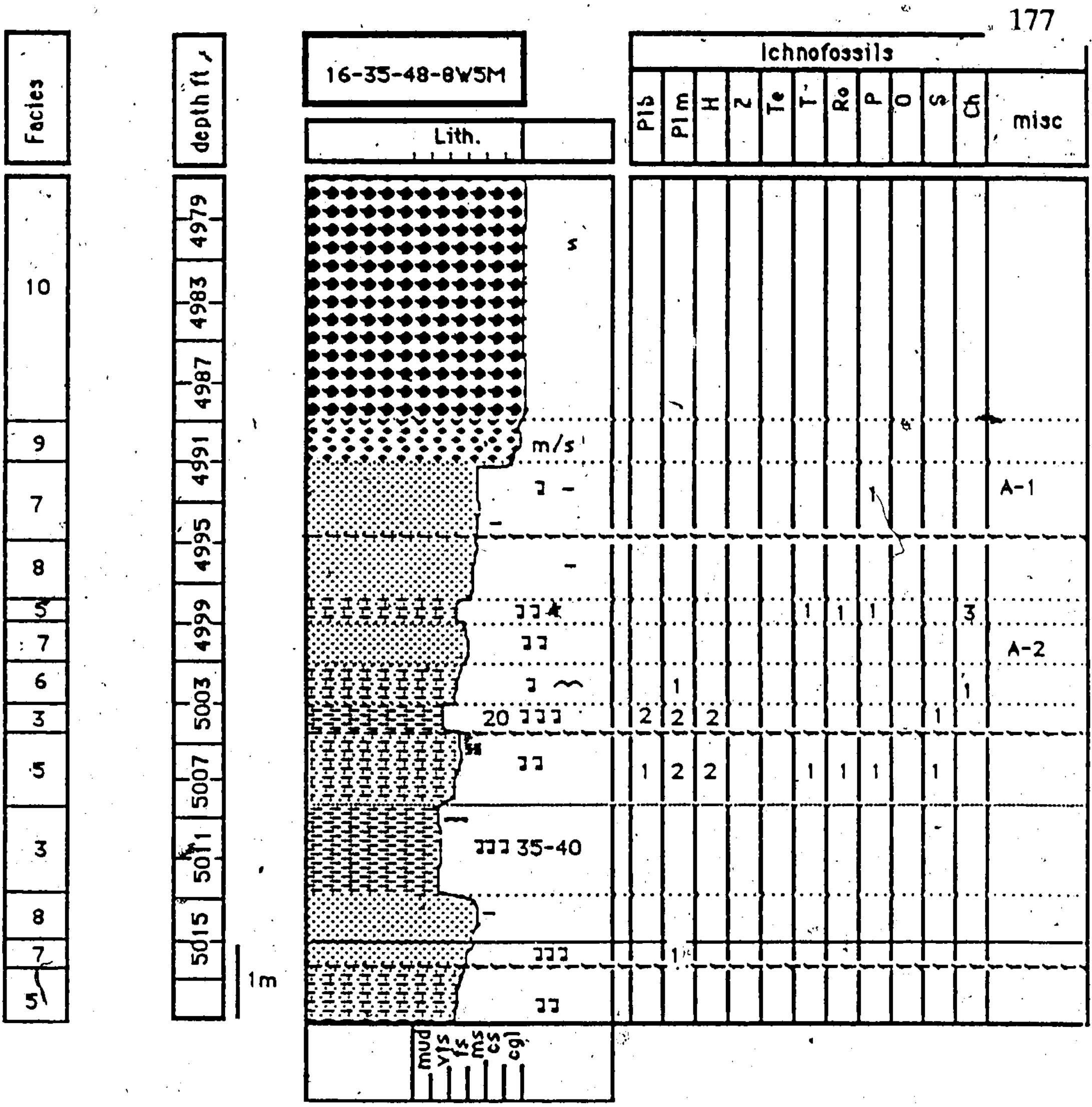
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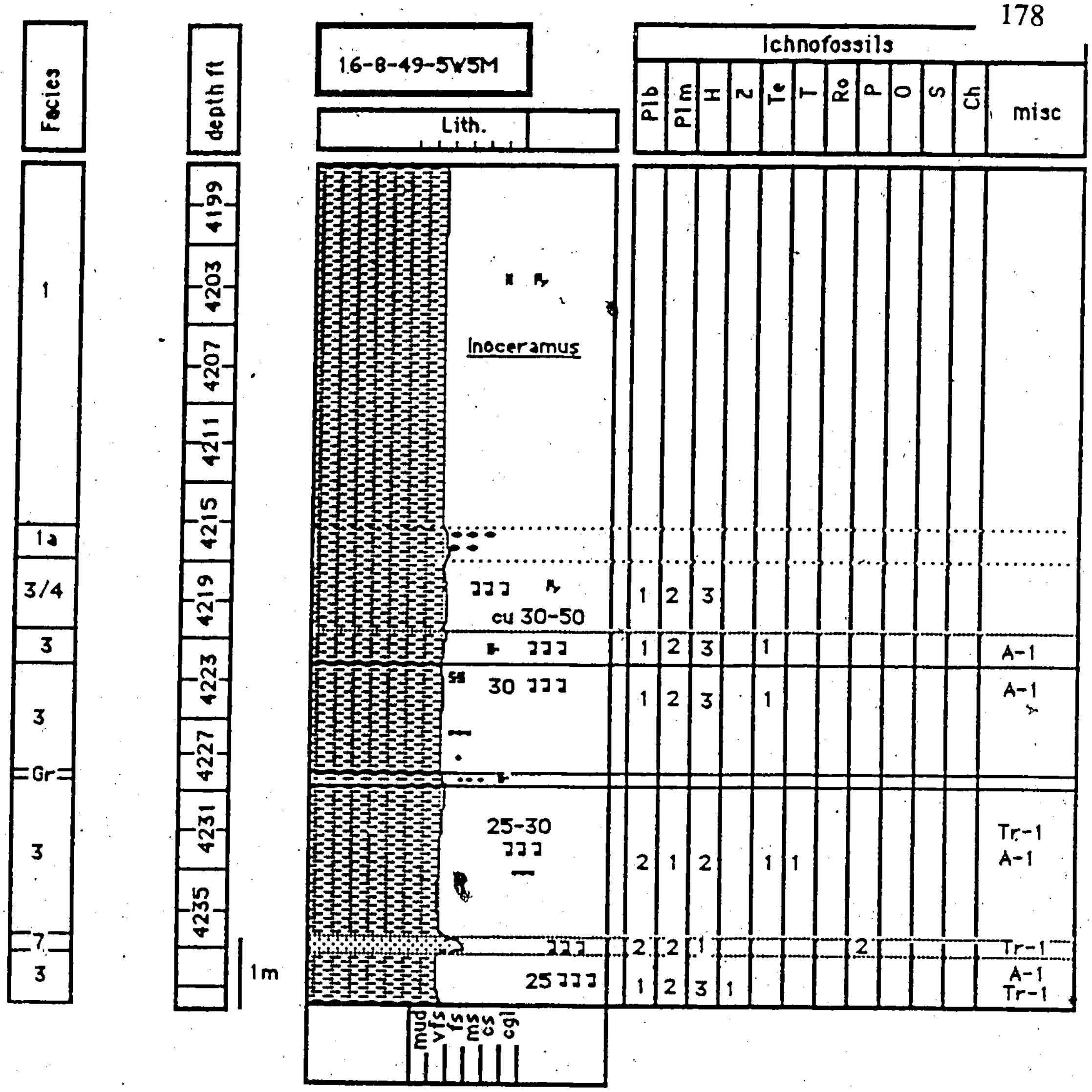
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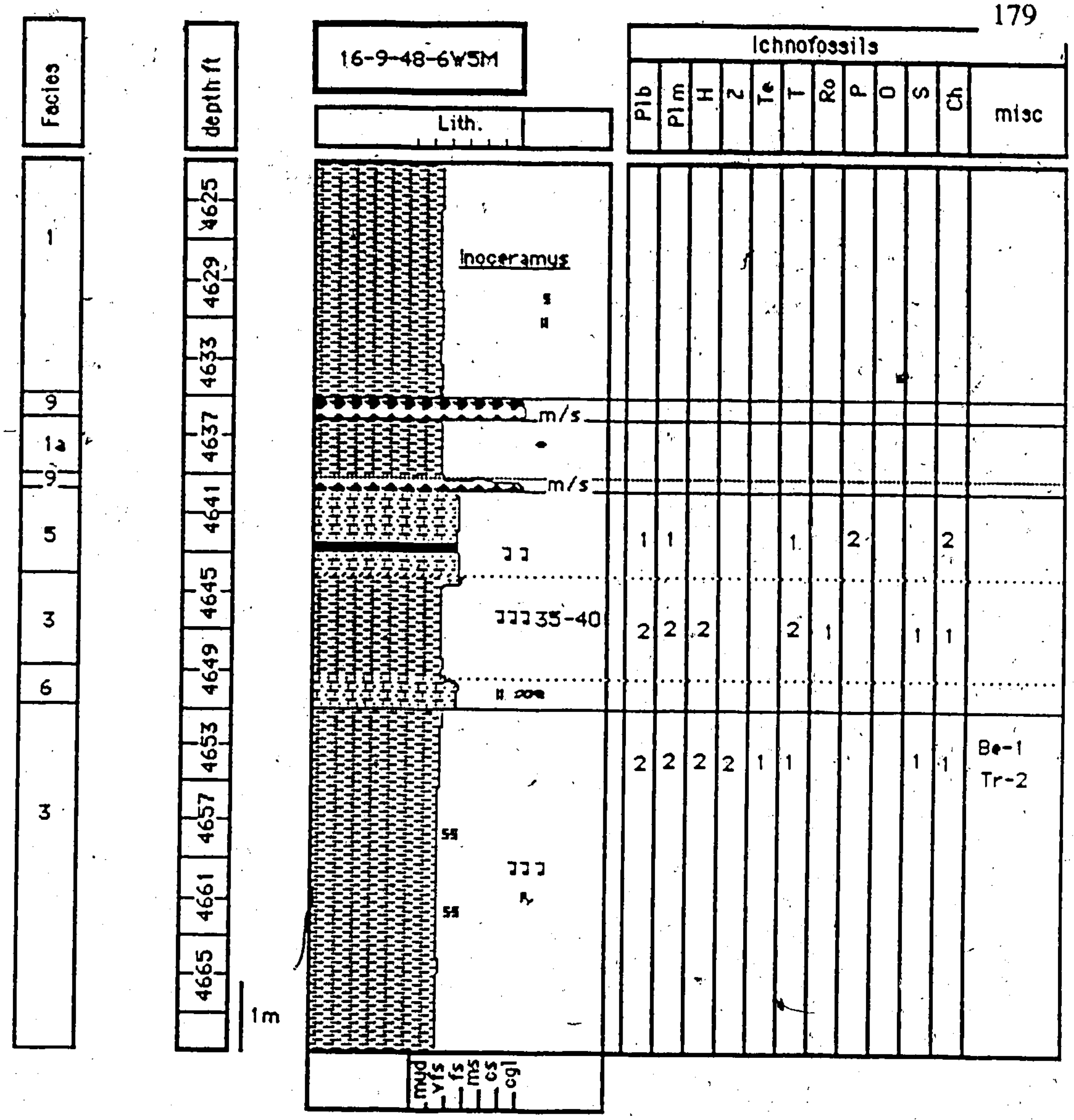
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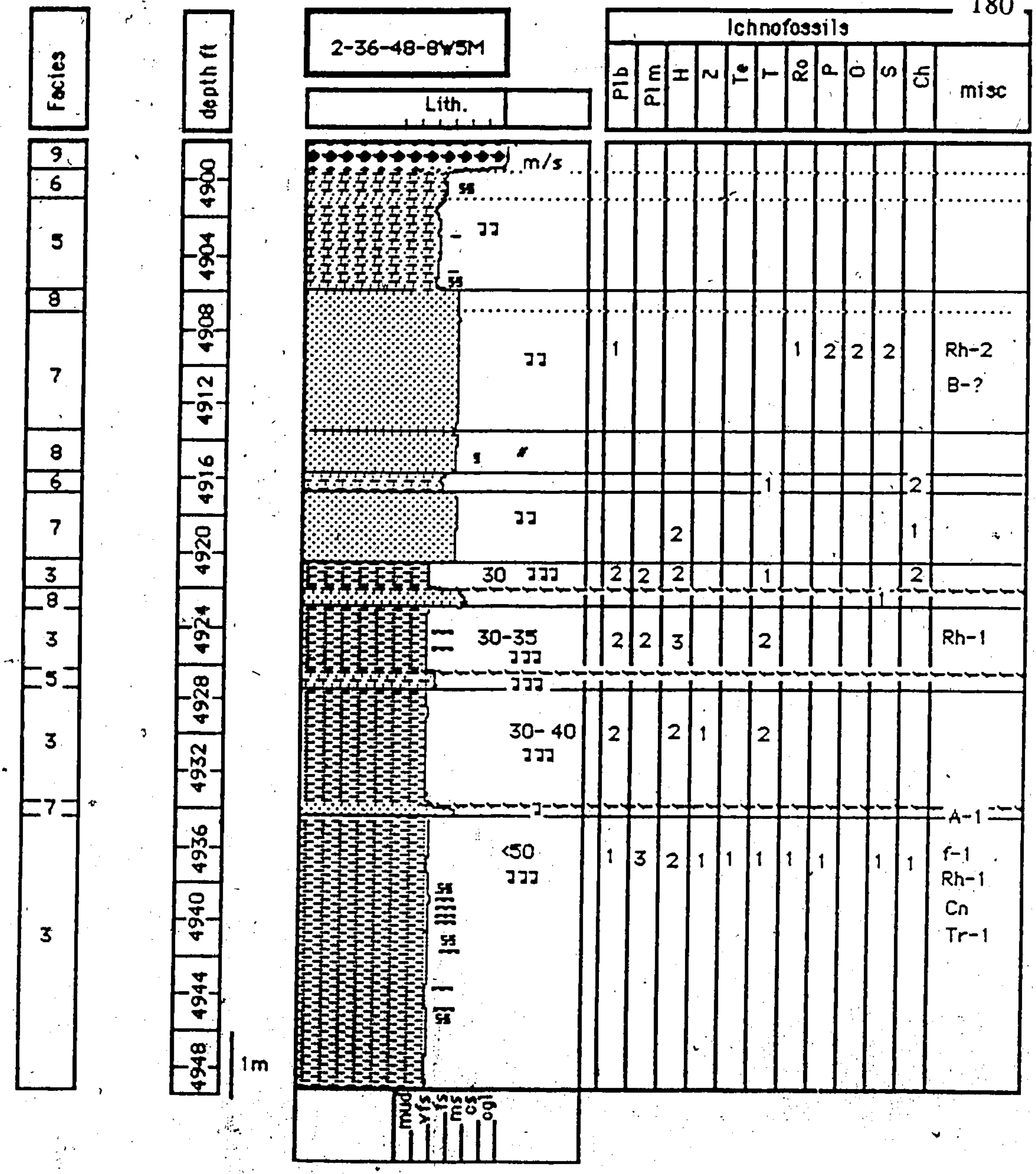
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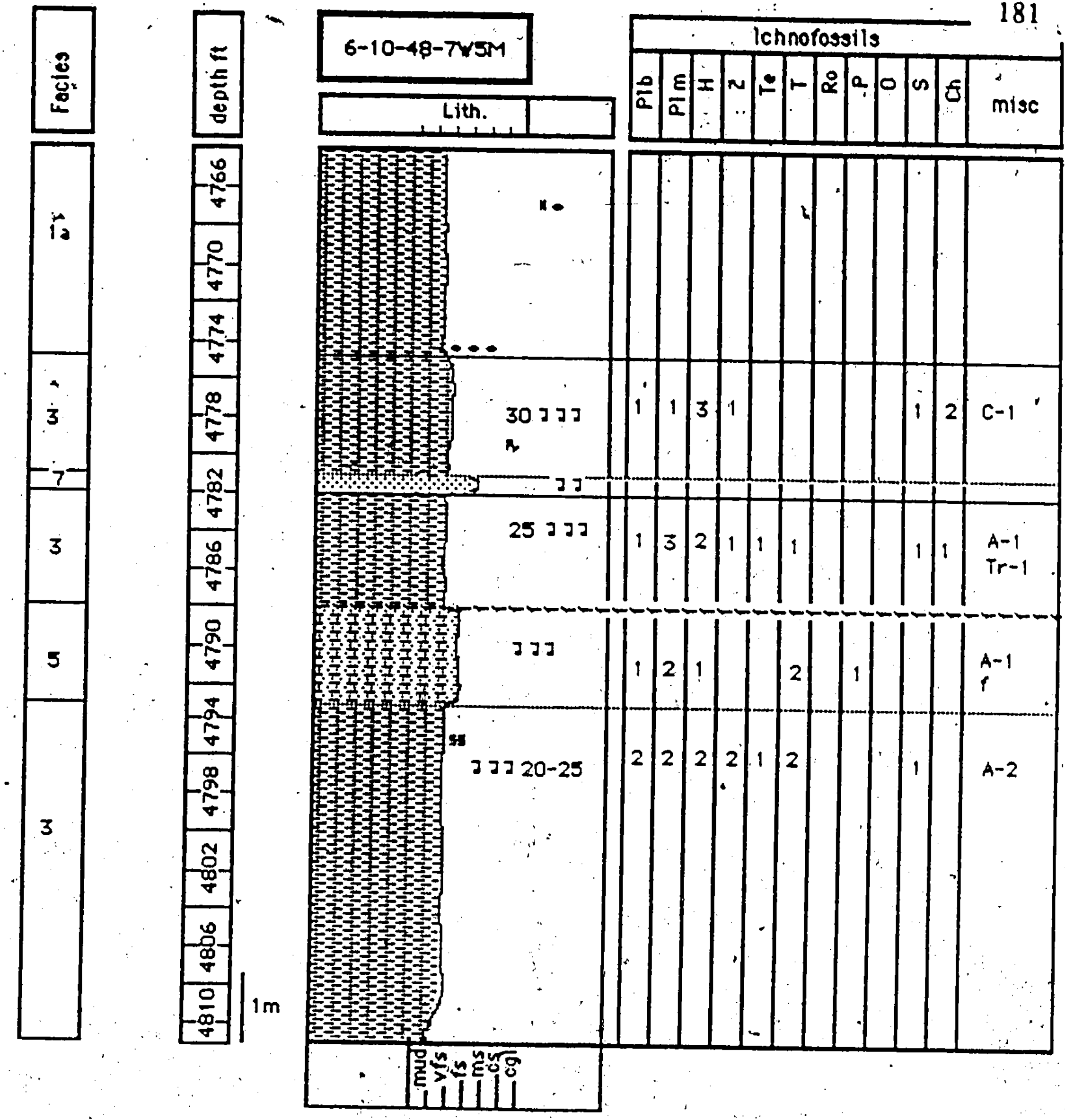
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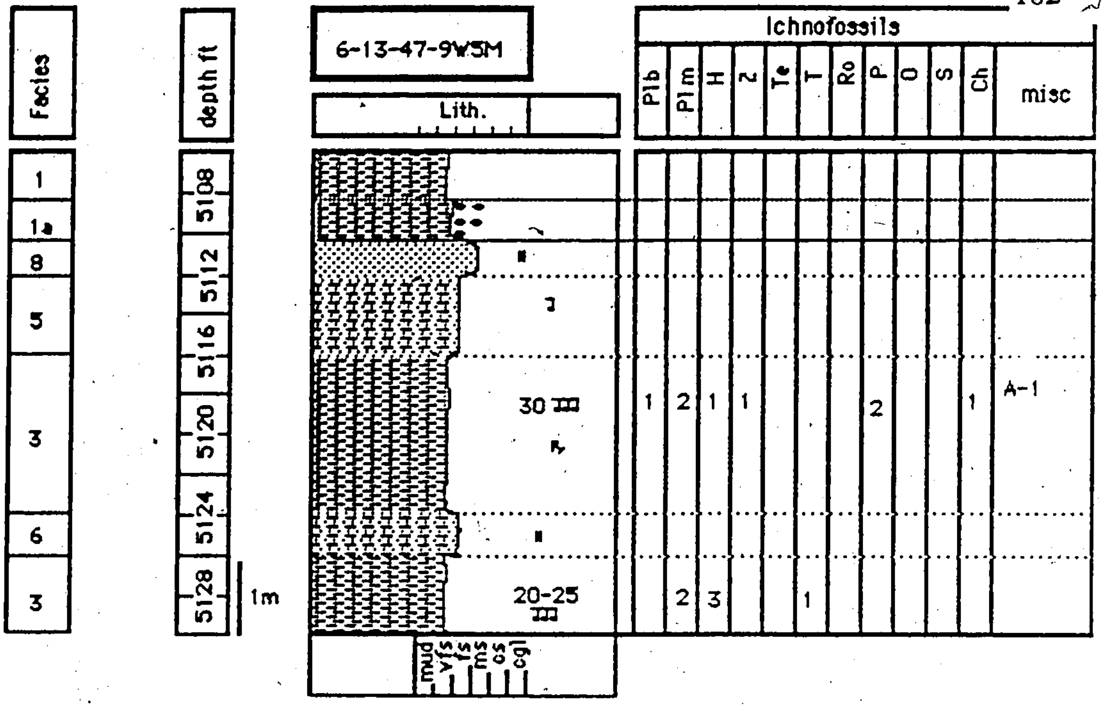
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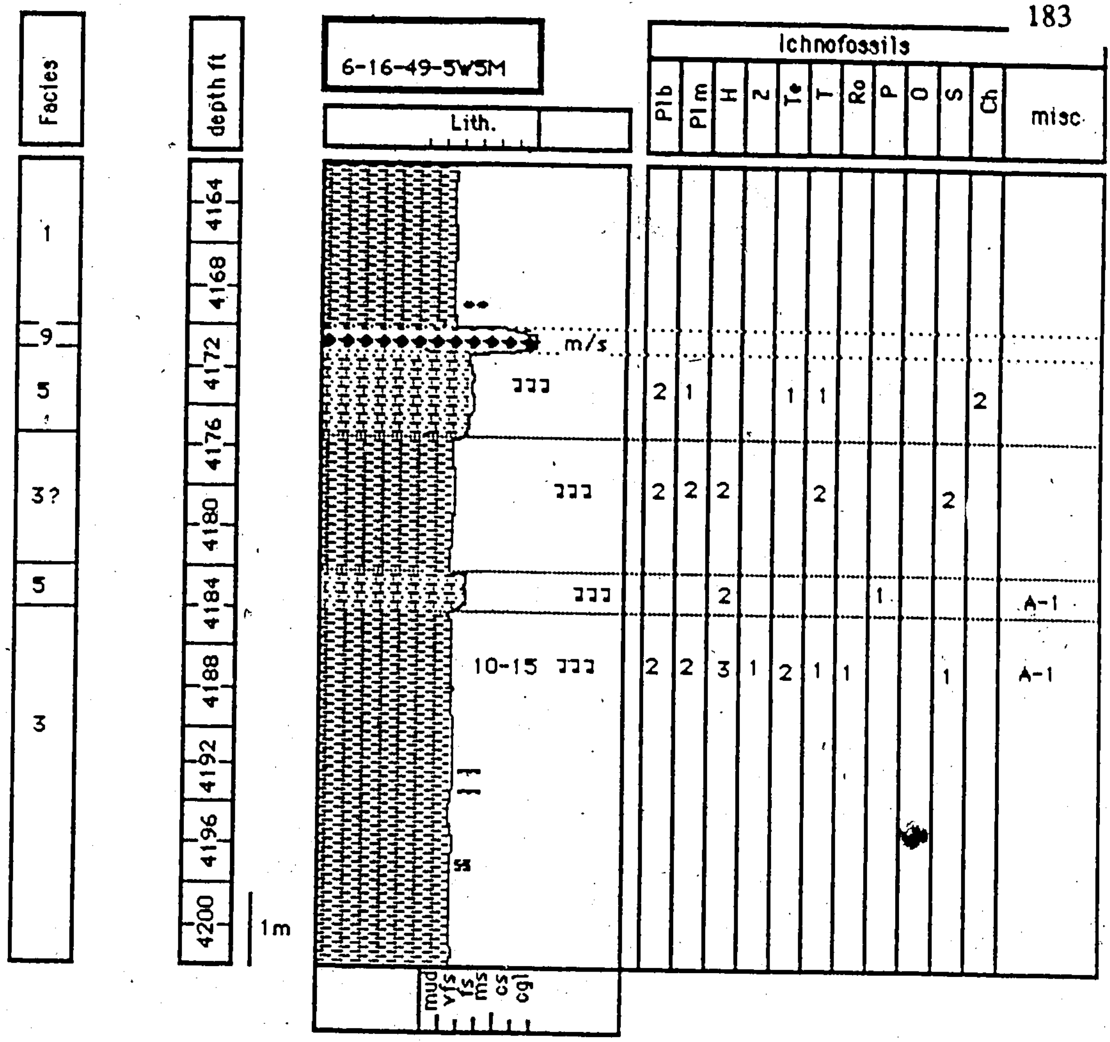
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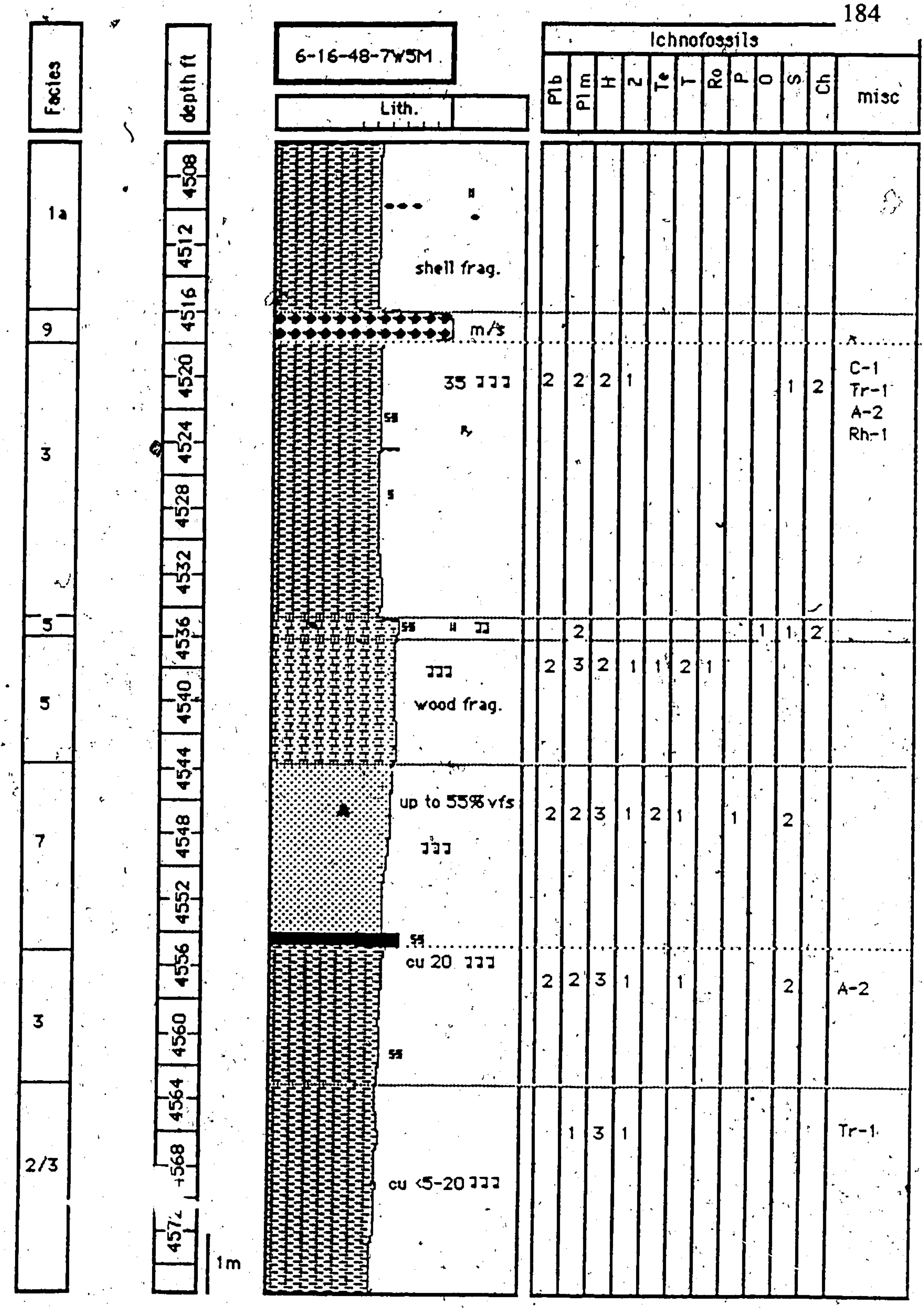
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shell frag.
m/s
35
wood frag.
up to 55% vfs
cu 20
cu <5-20
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C-1
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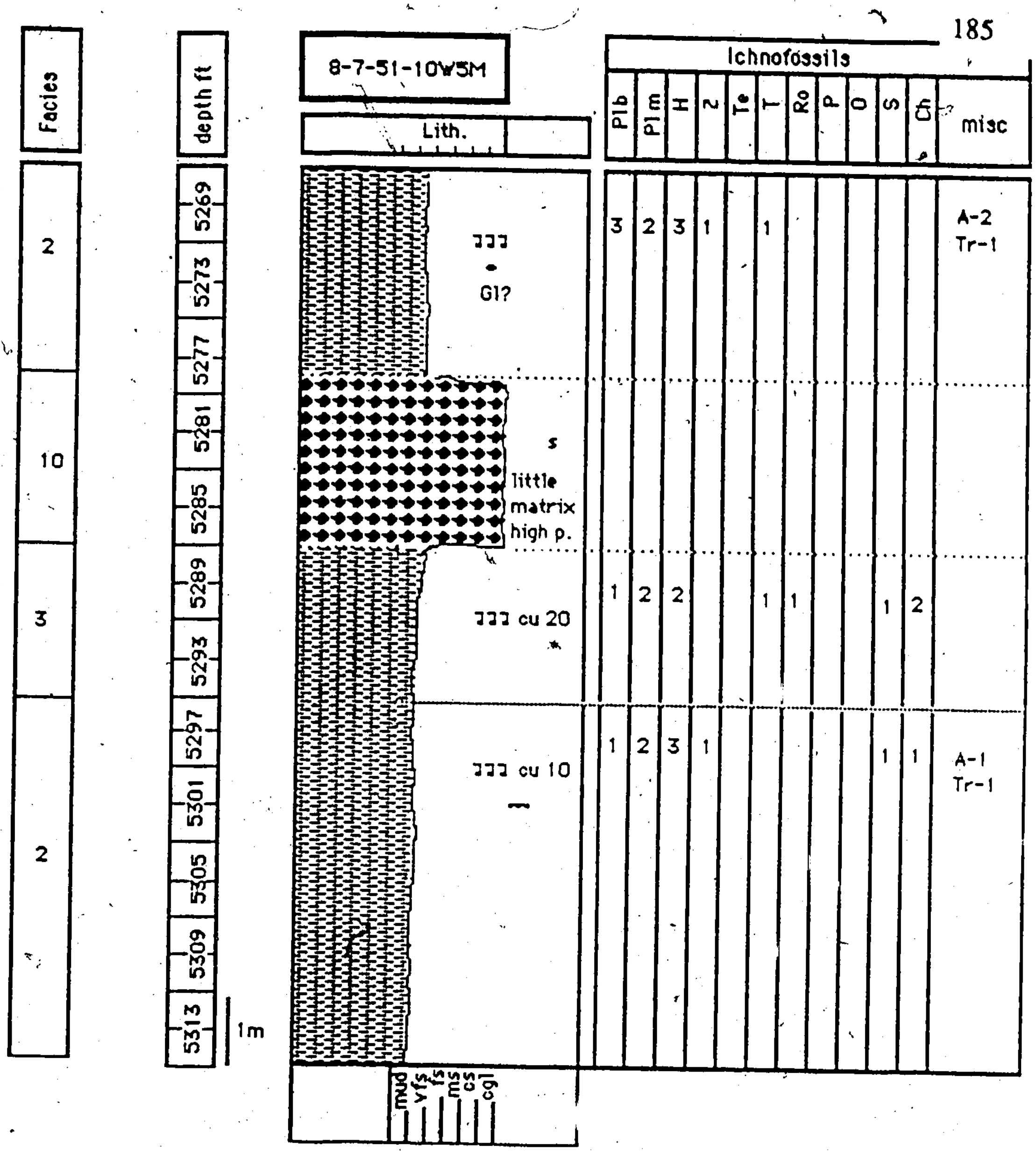
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T
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P
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S
Ch
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GI?
s
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high p.
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cu 10
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Tr-1
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Tr-1
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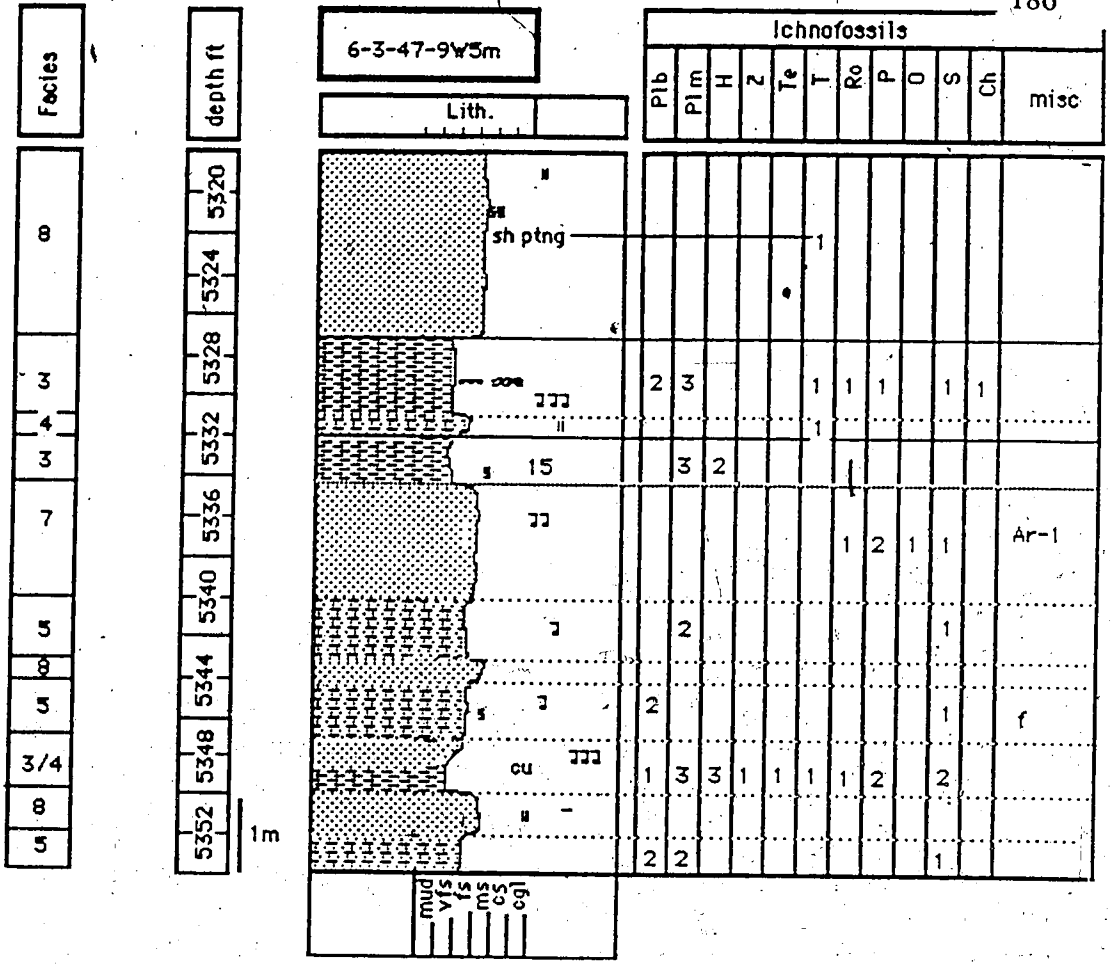
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1m
6-3-47-9W5m
Lith.
sh ptng
15
cu
mud
vfs
fs
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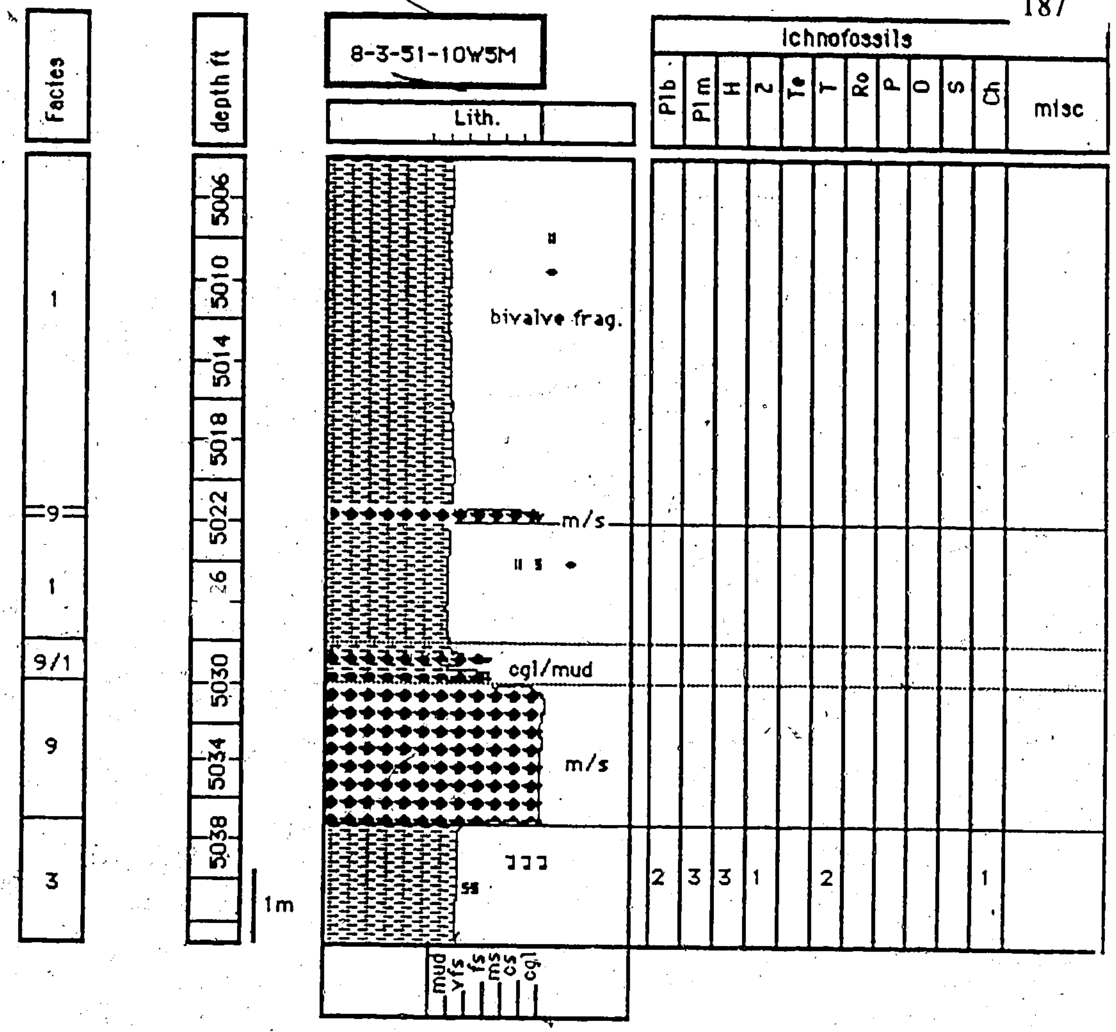
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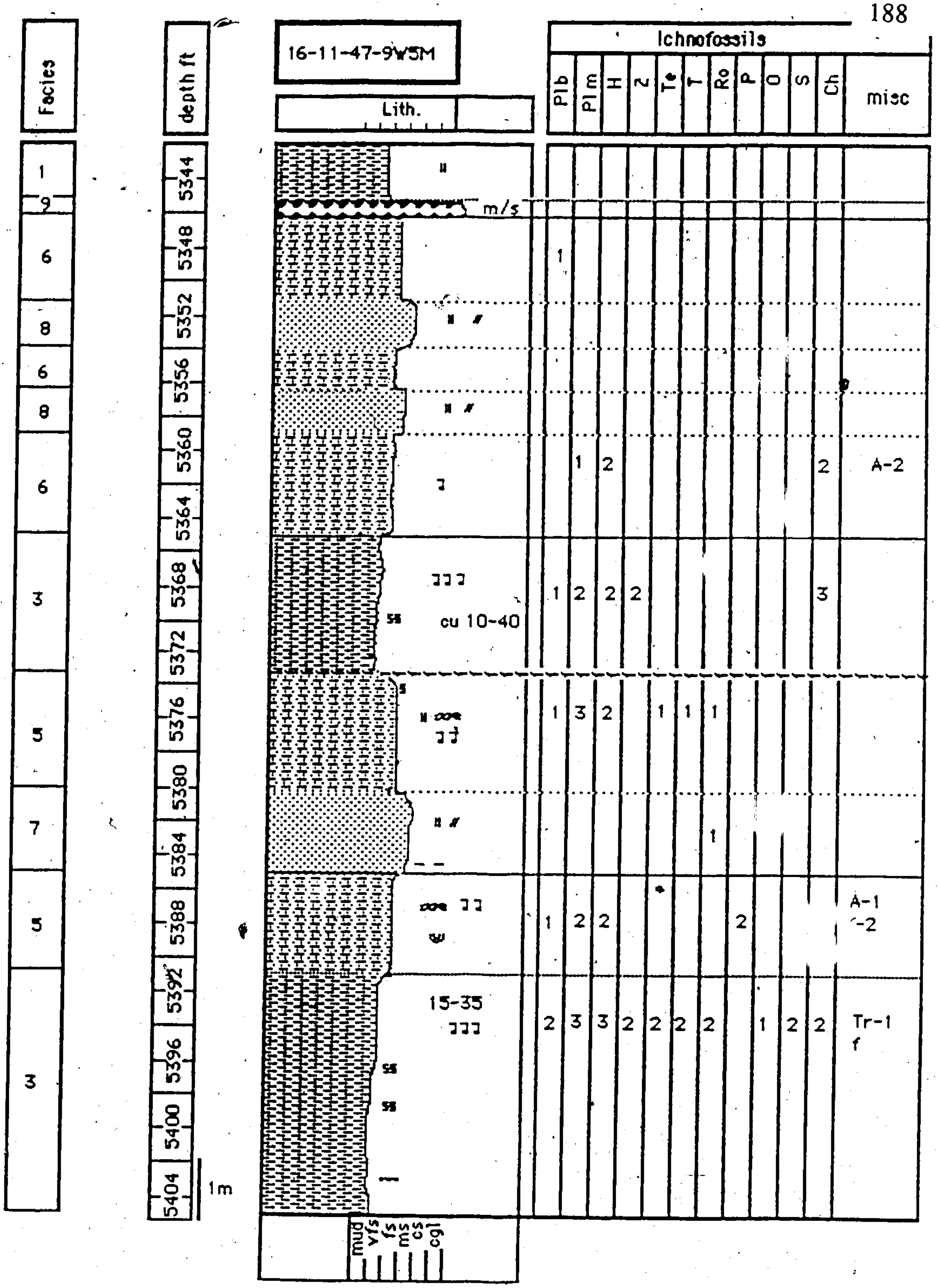
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m/s
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A-1
-2
Tr-1
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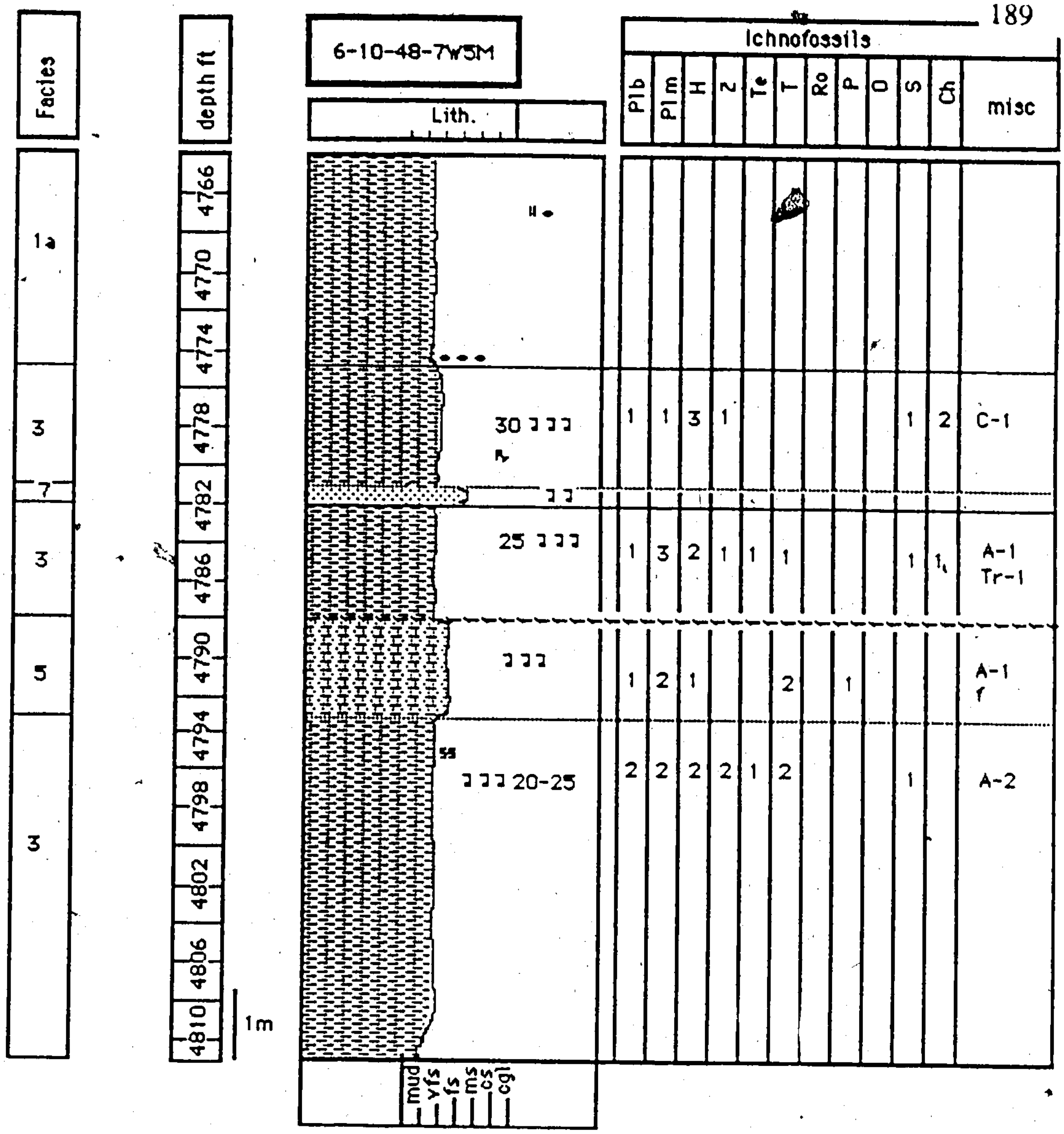
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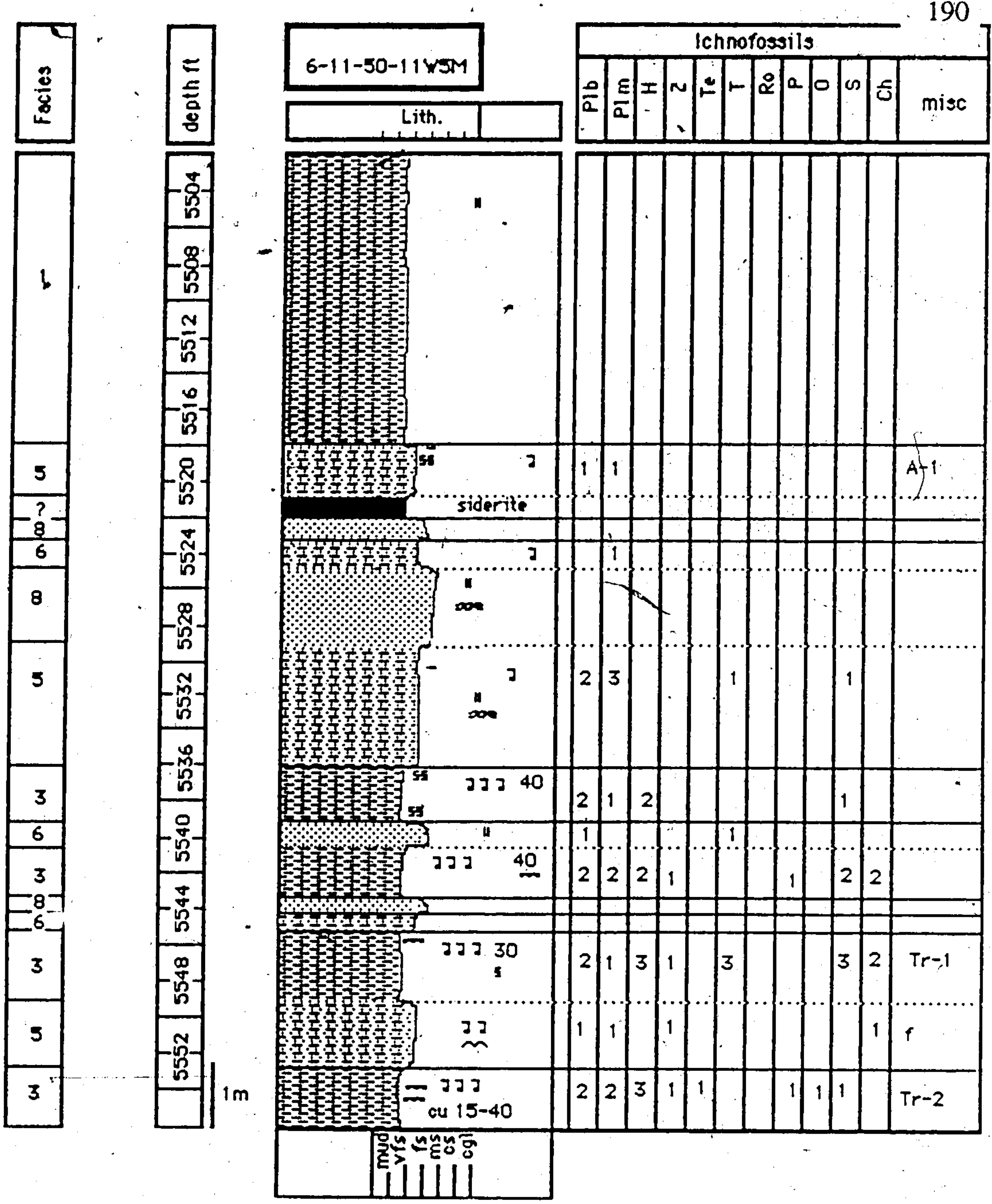
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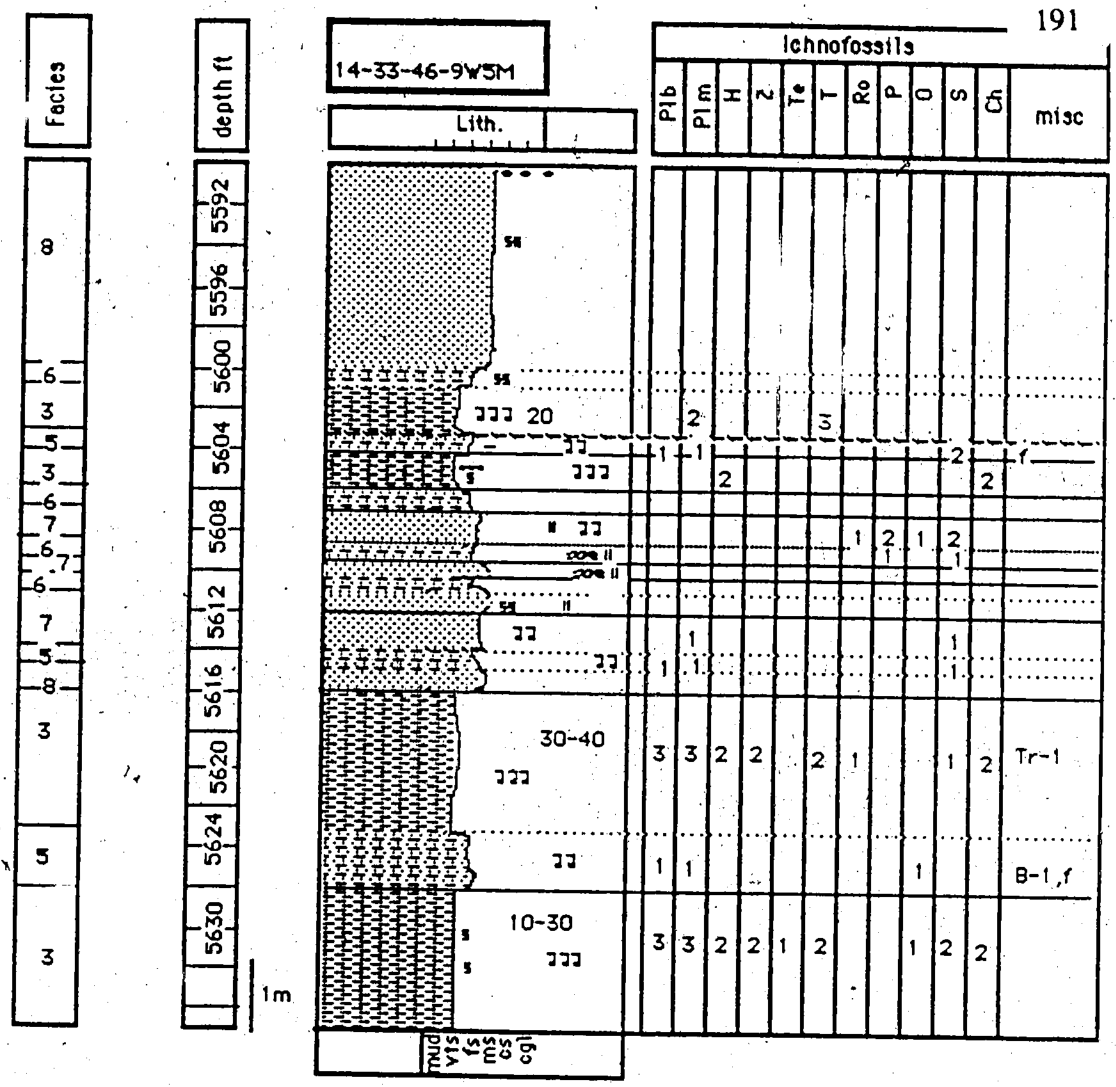
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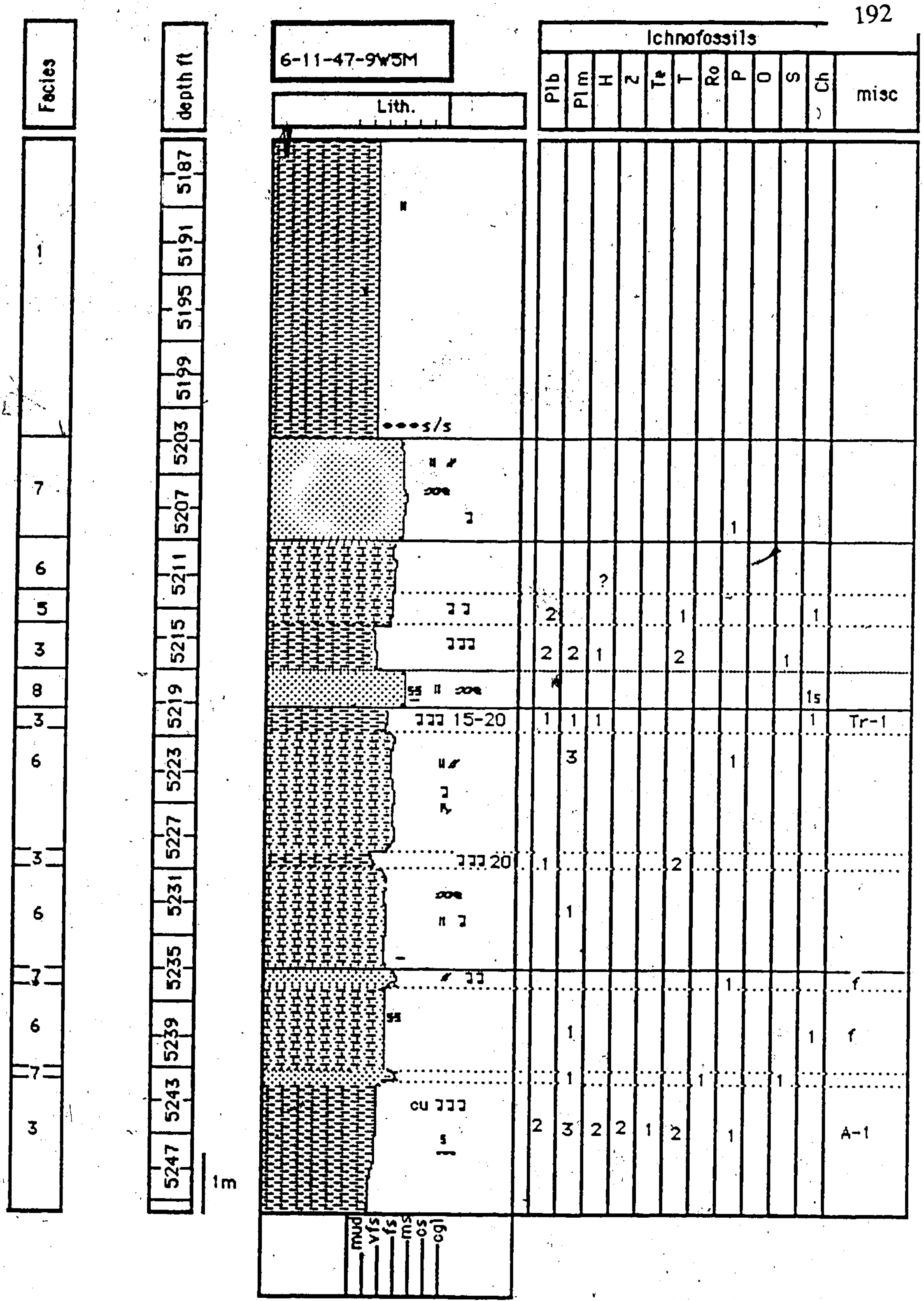
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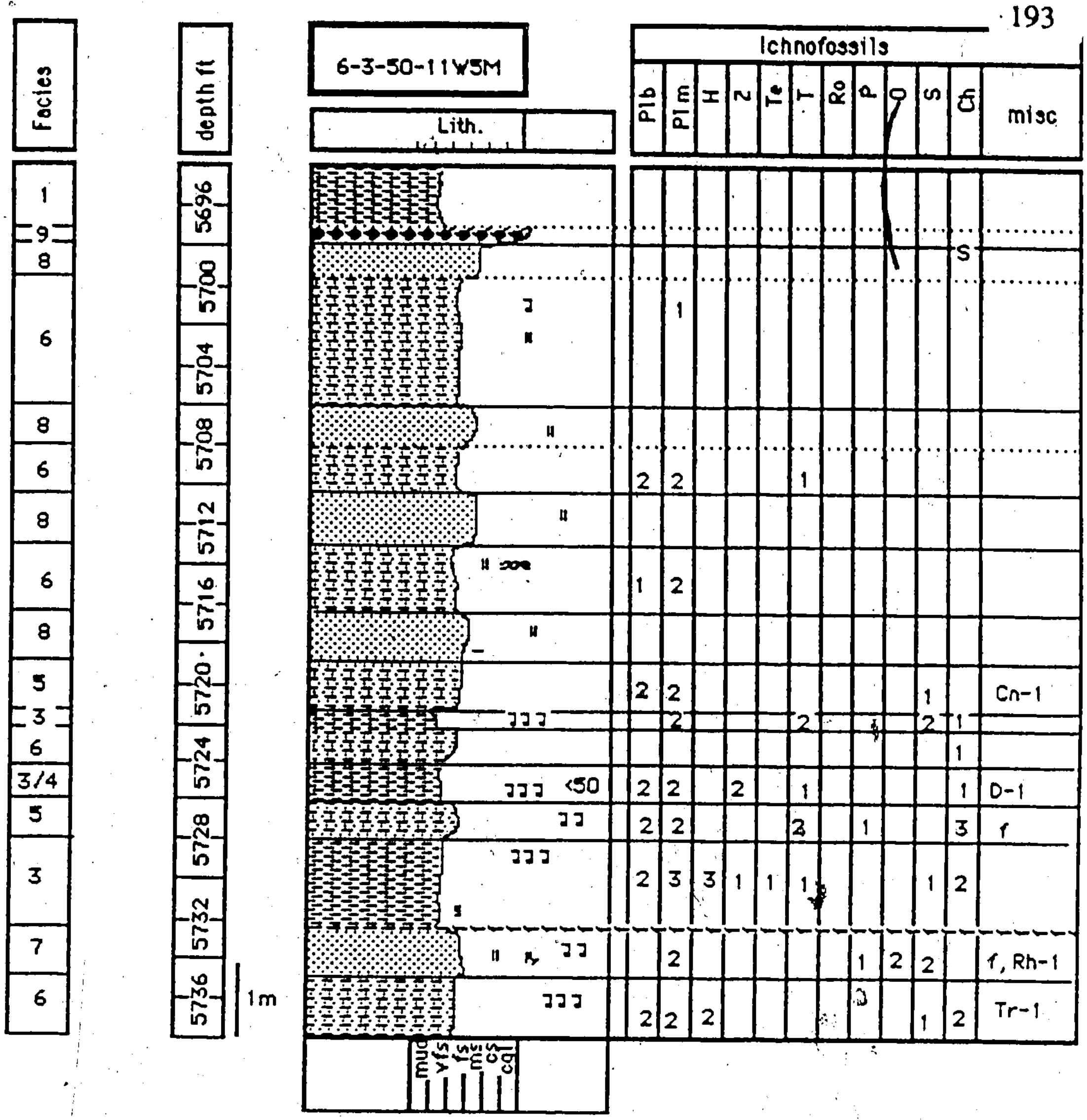
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Ch
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Tr-1
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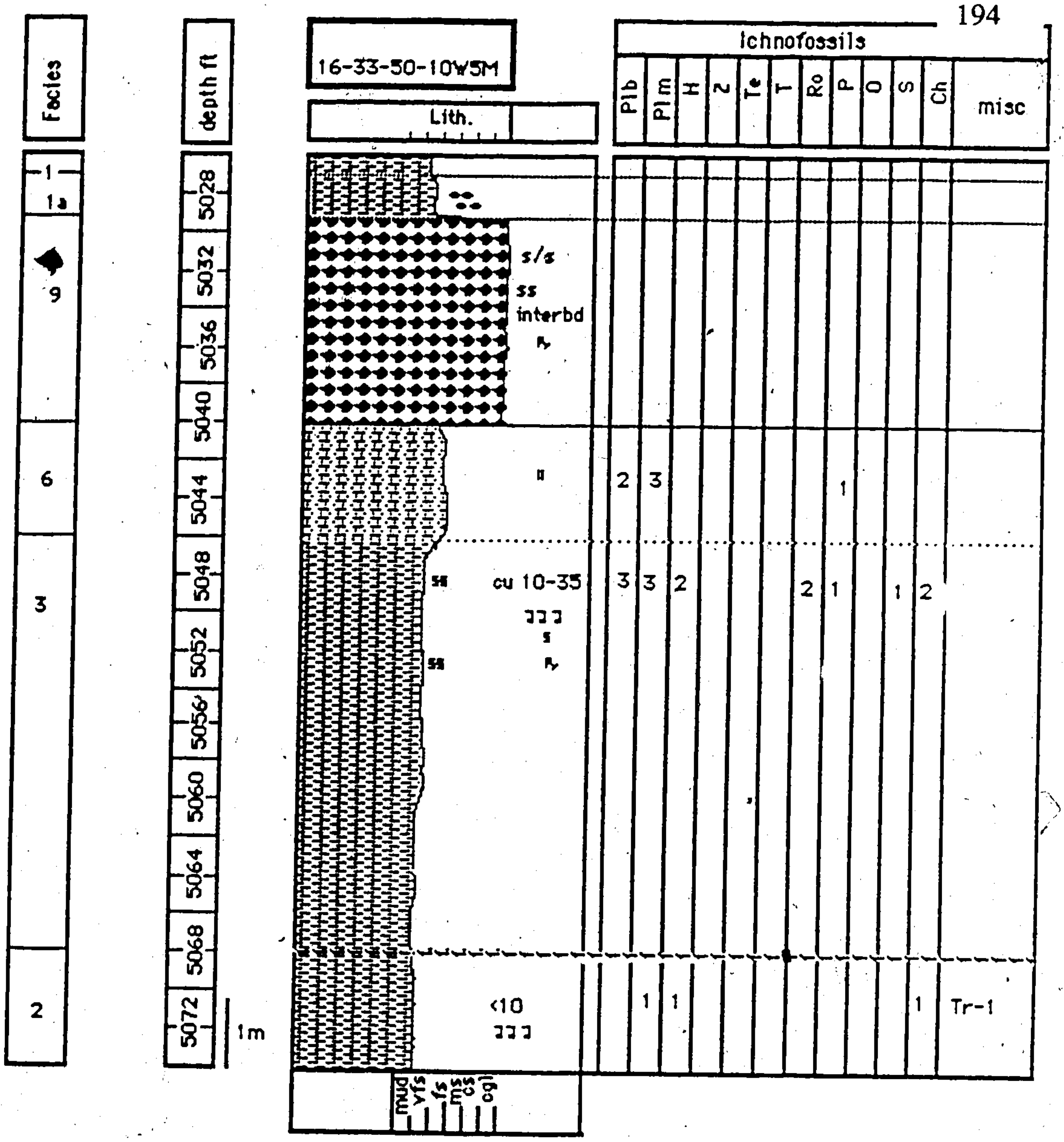
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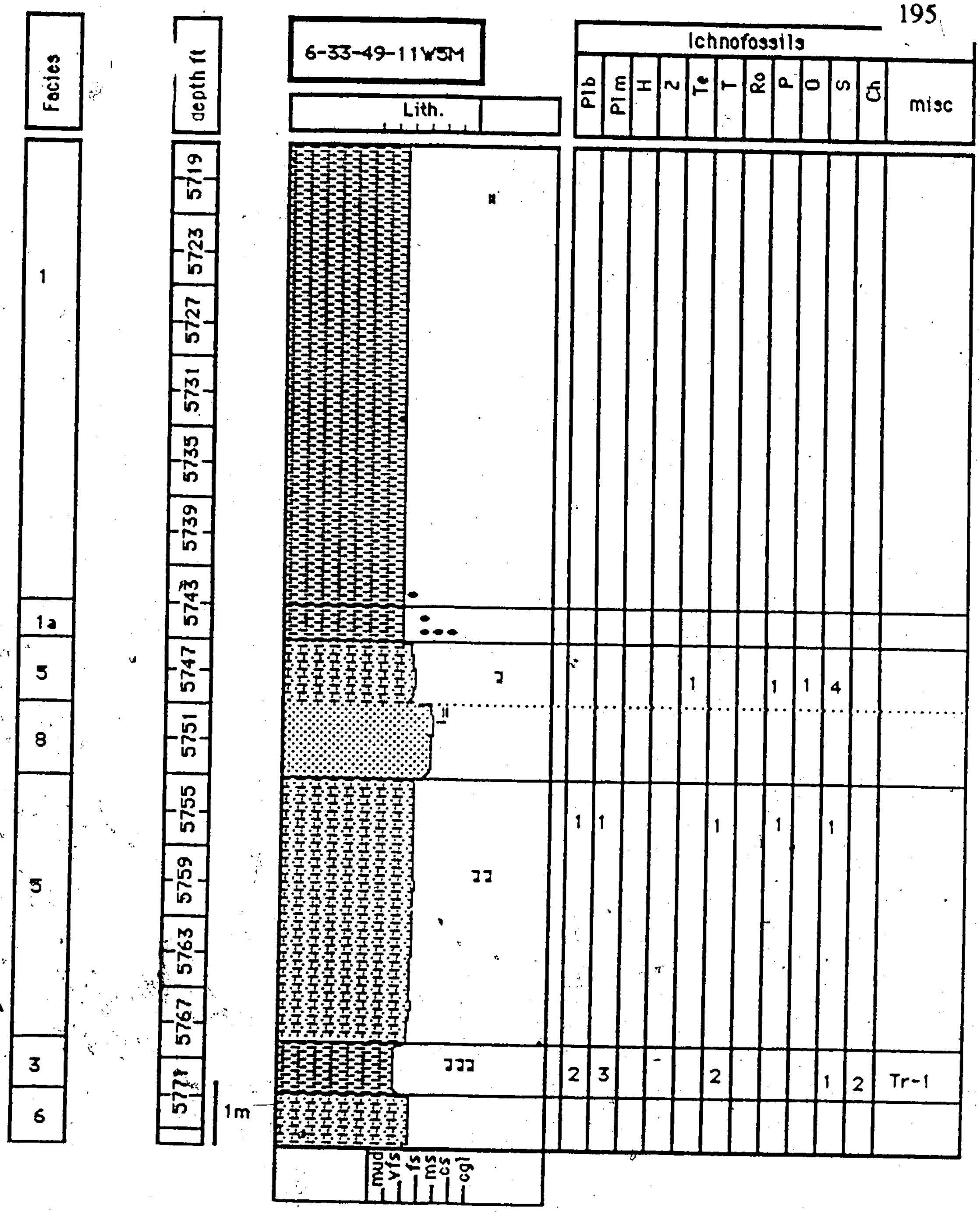
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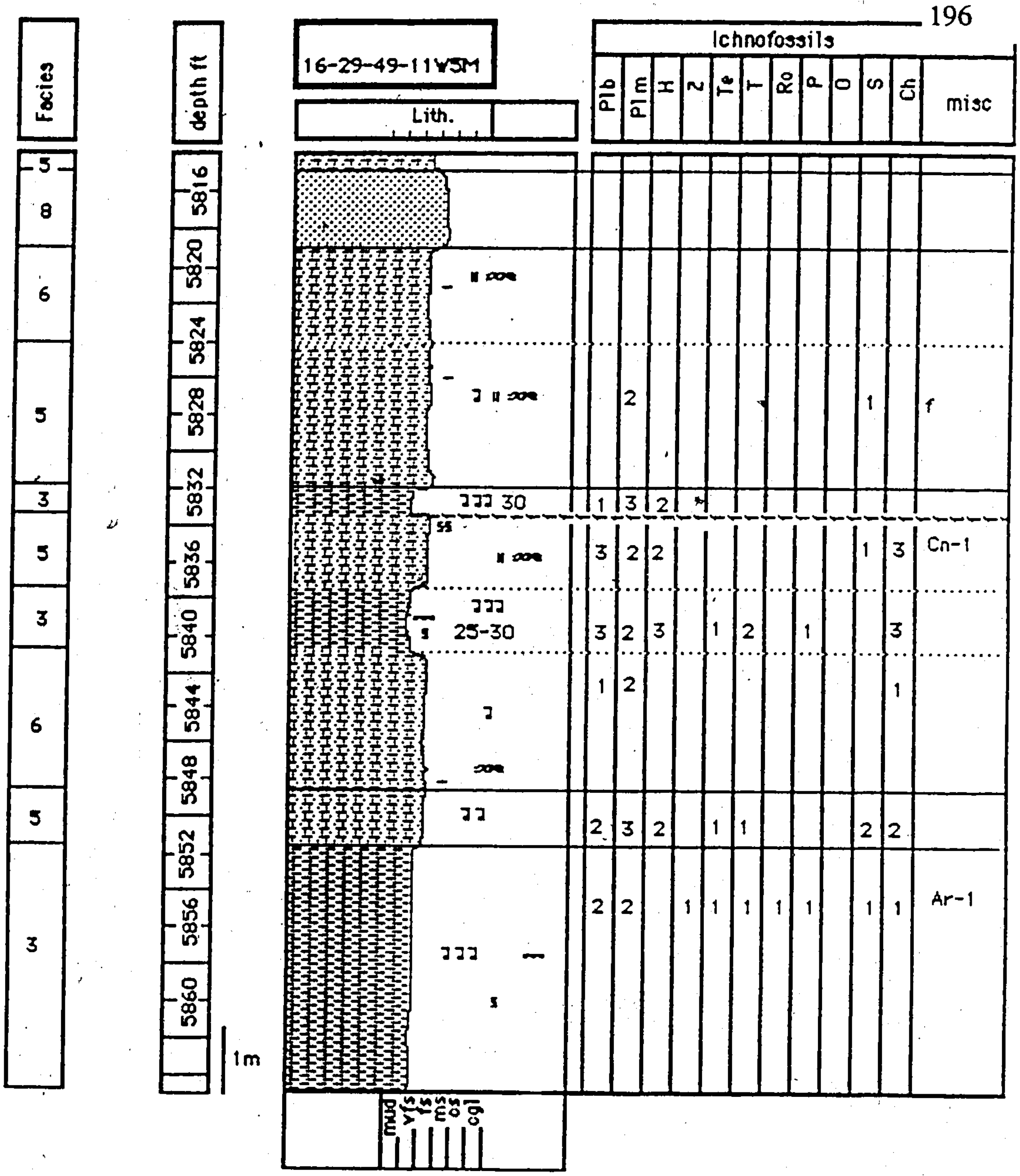
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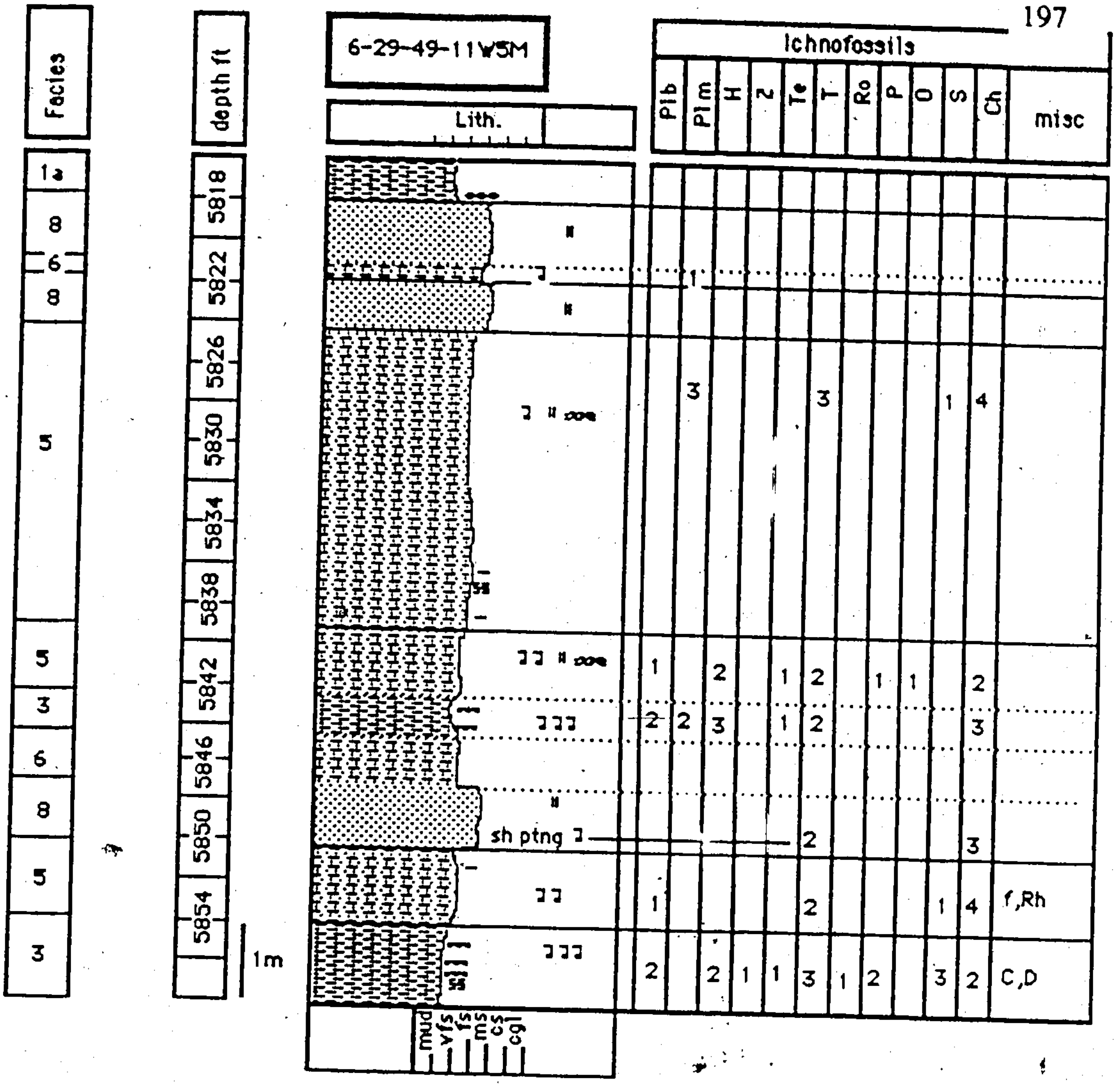
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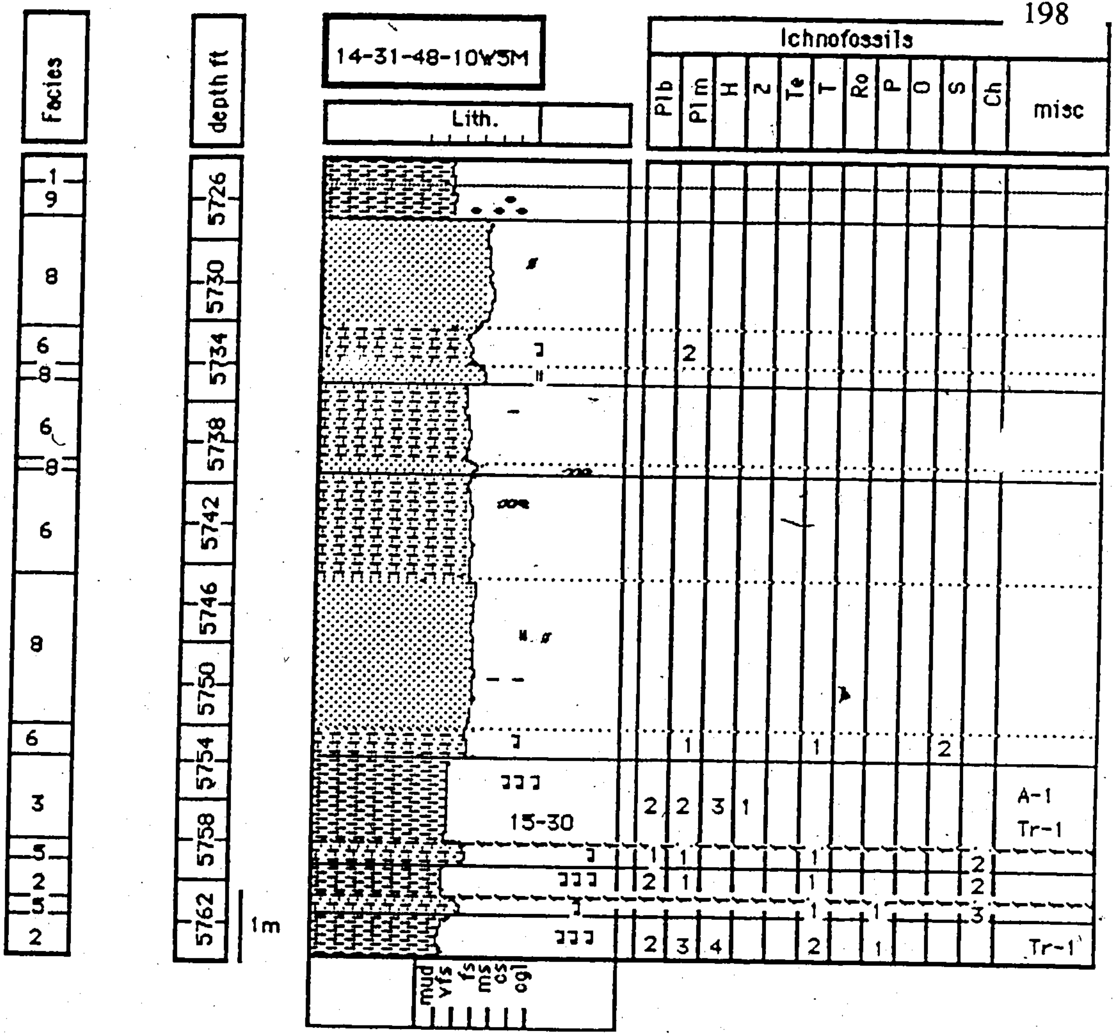
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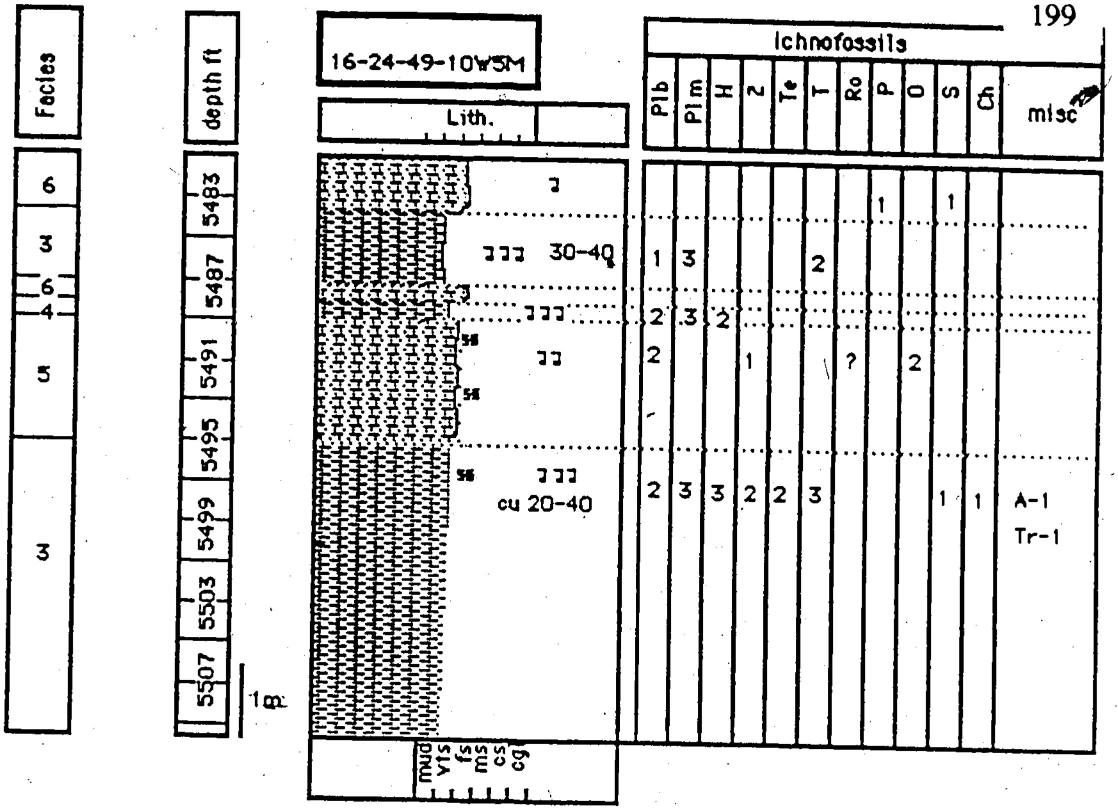
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Tr-1
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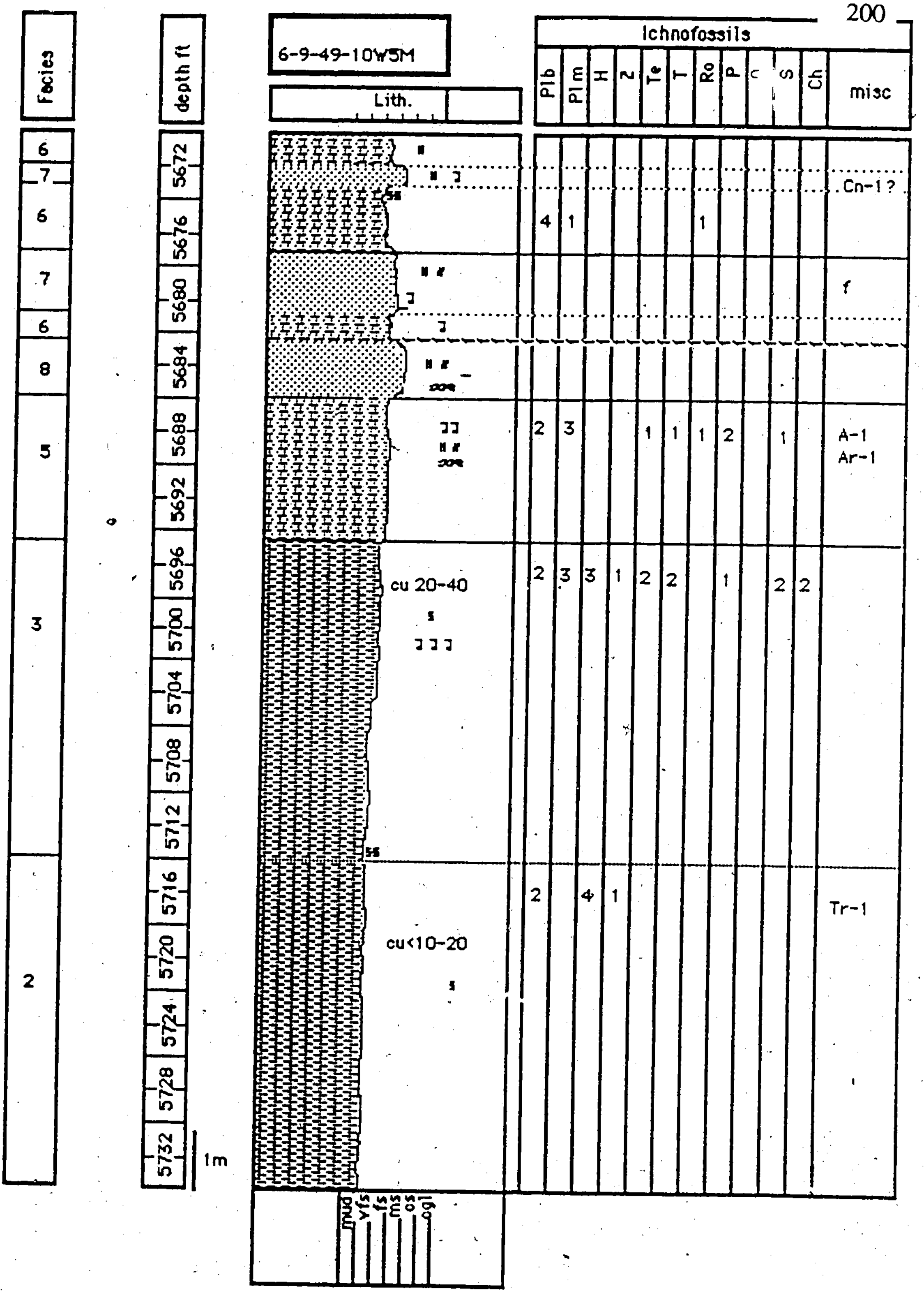
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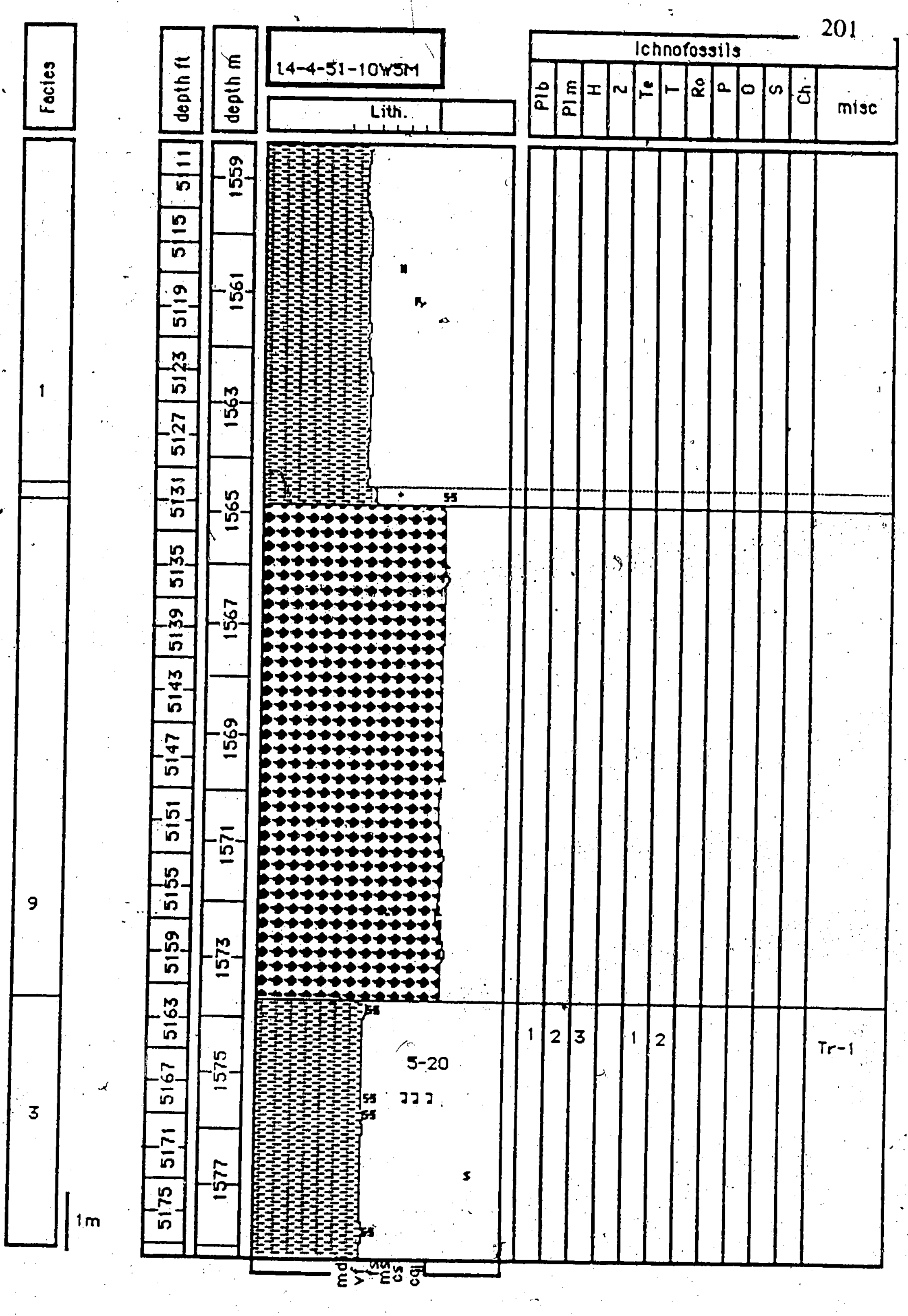
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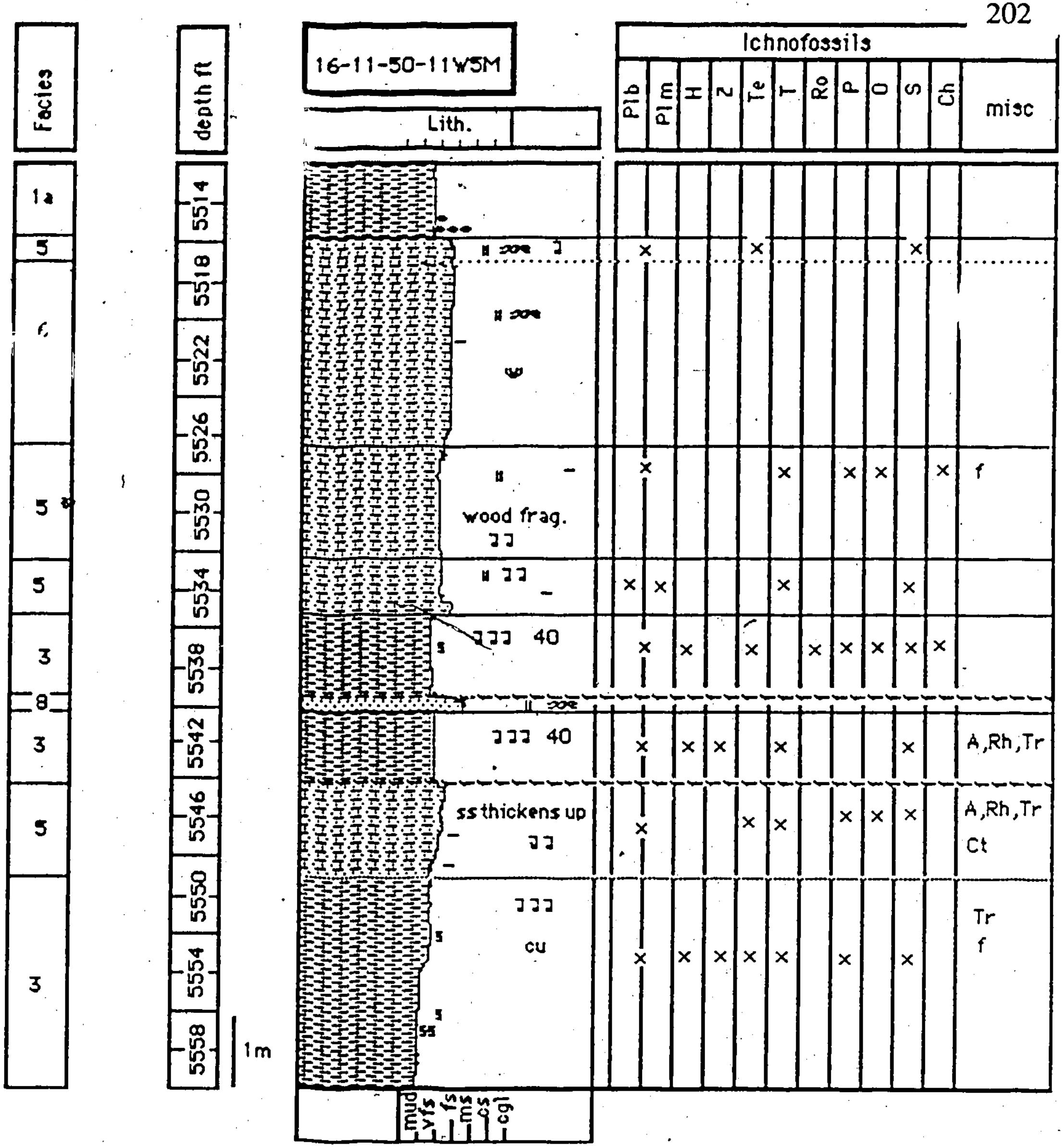
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Ch
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Tr
f
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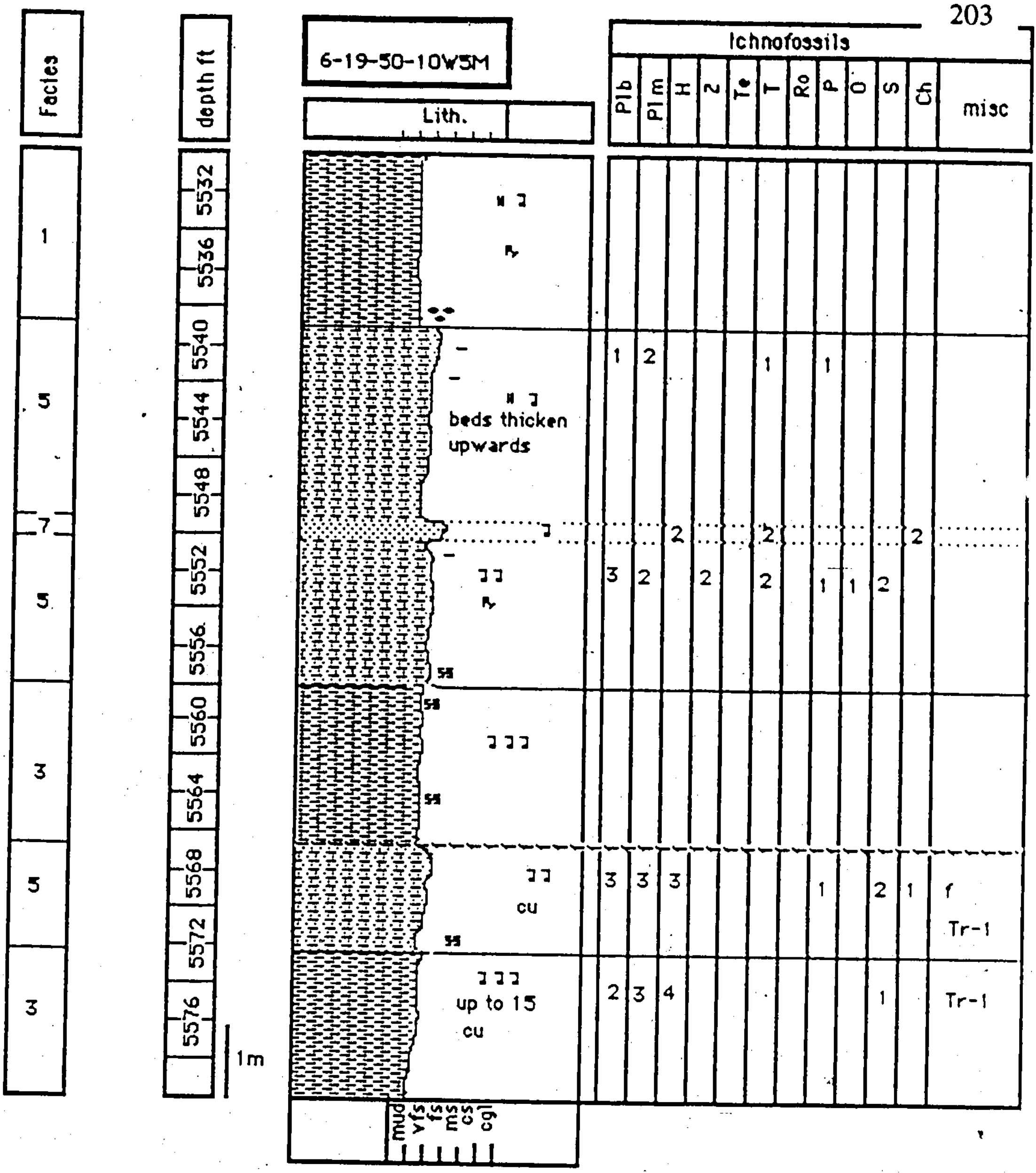
ms
cs
cgl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P
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S
Ch
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1m
beds thicken upwards
cu
up to 15
cu
mud
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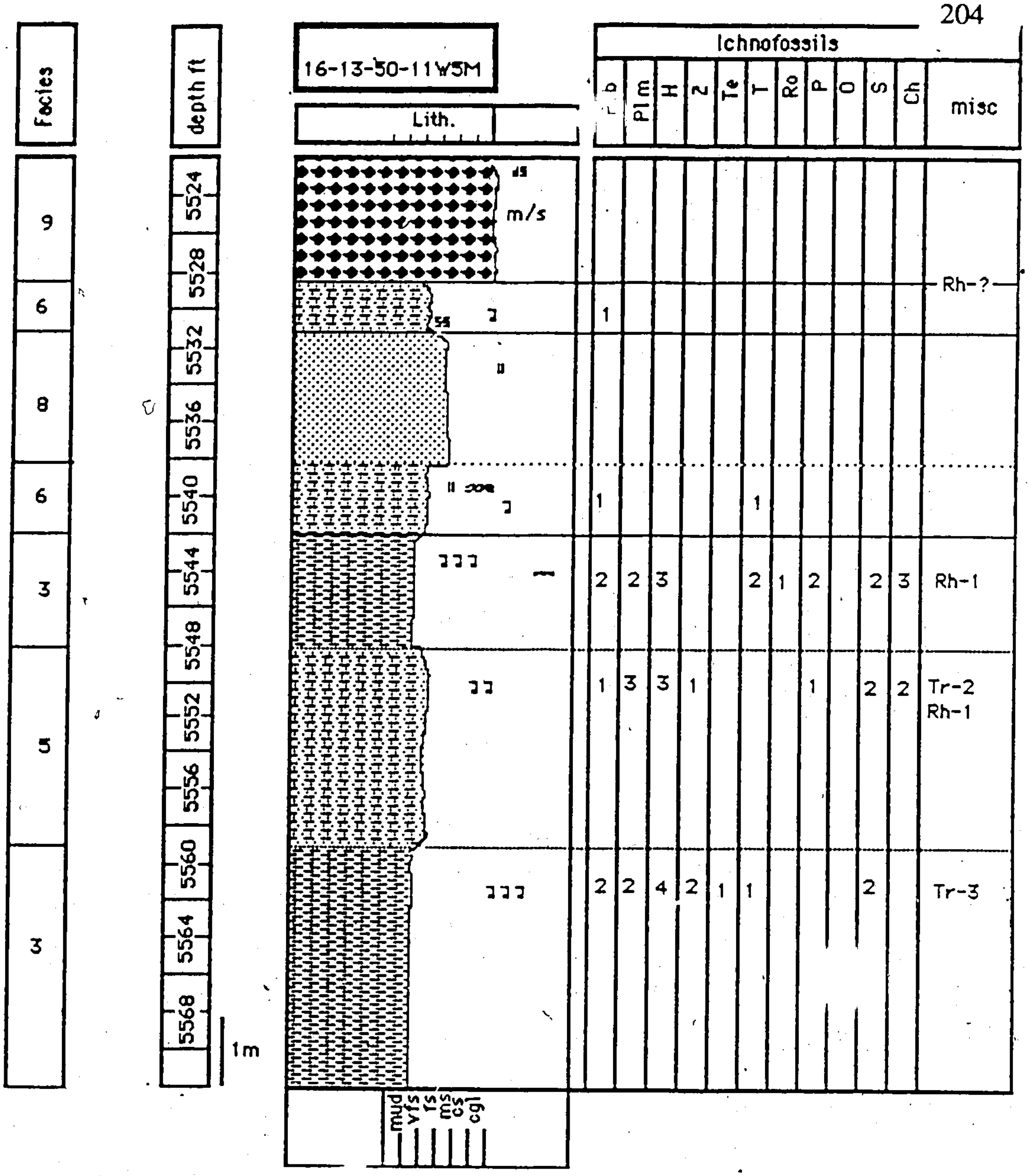
Tr-1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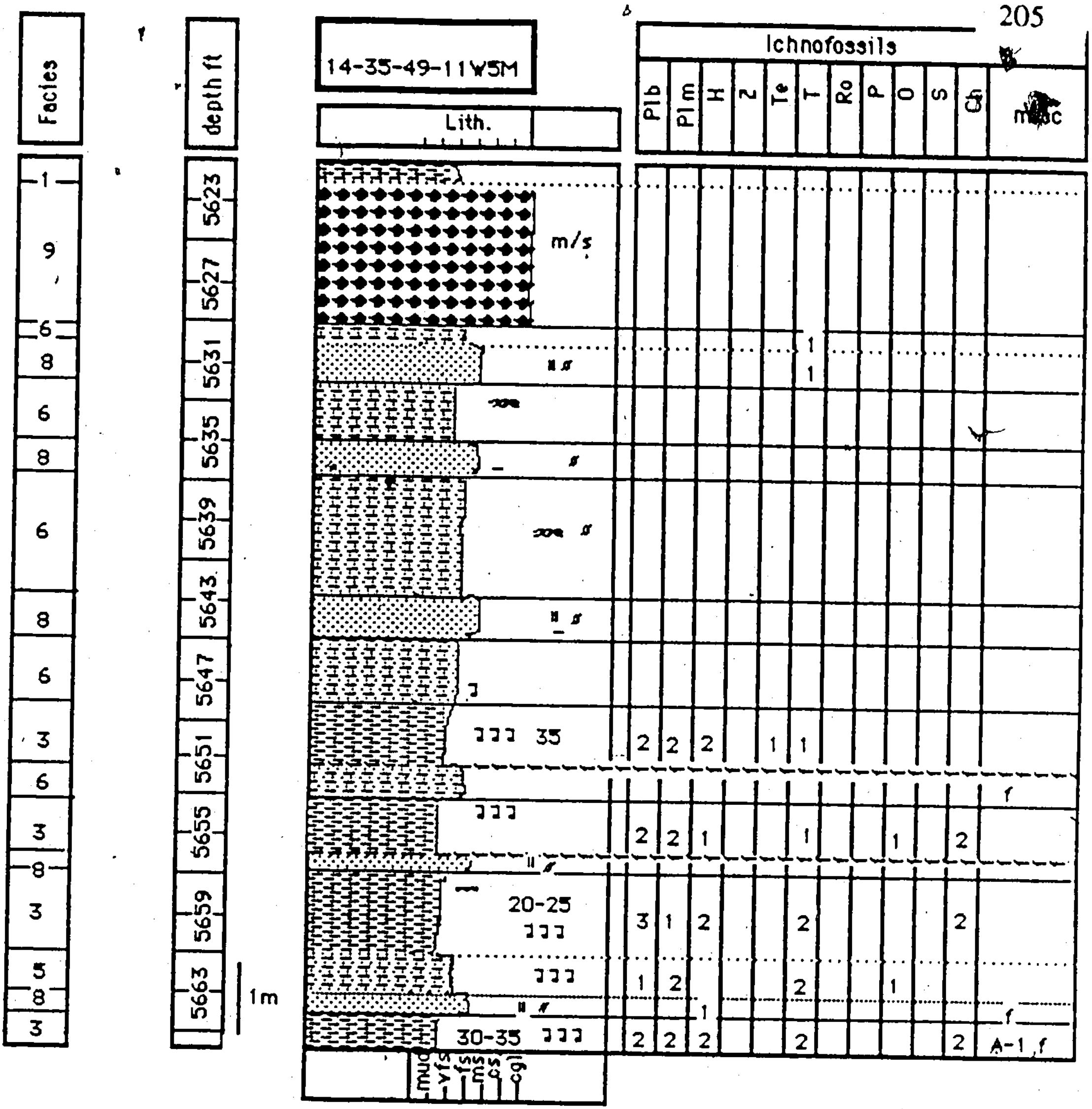
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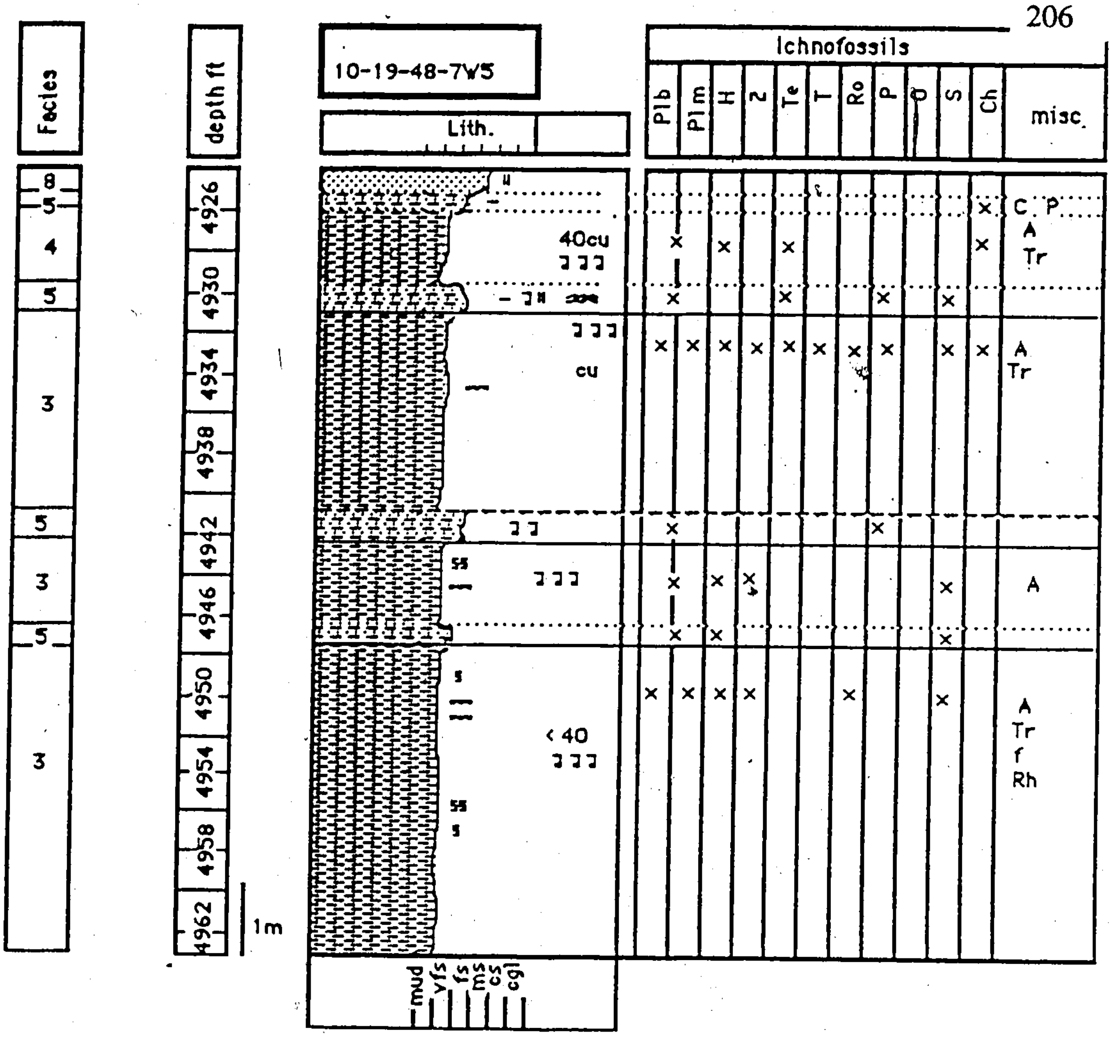
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Rh
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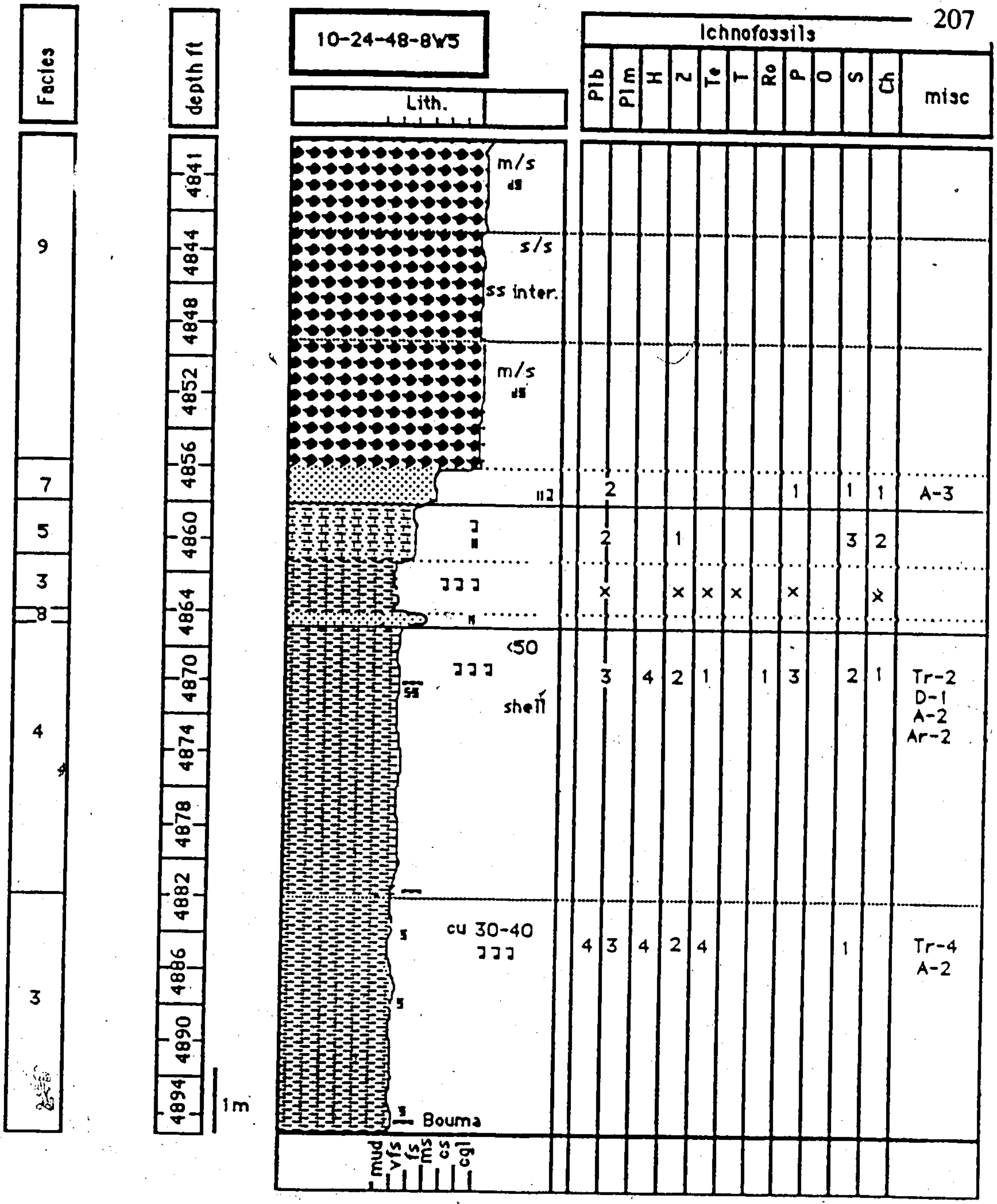
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Ch
misc
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s/s
ss inter.
m/s
<50
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cu 30-40
Bouma
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vfs
fs
ms
cs
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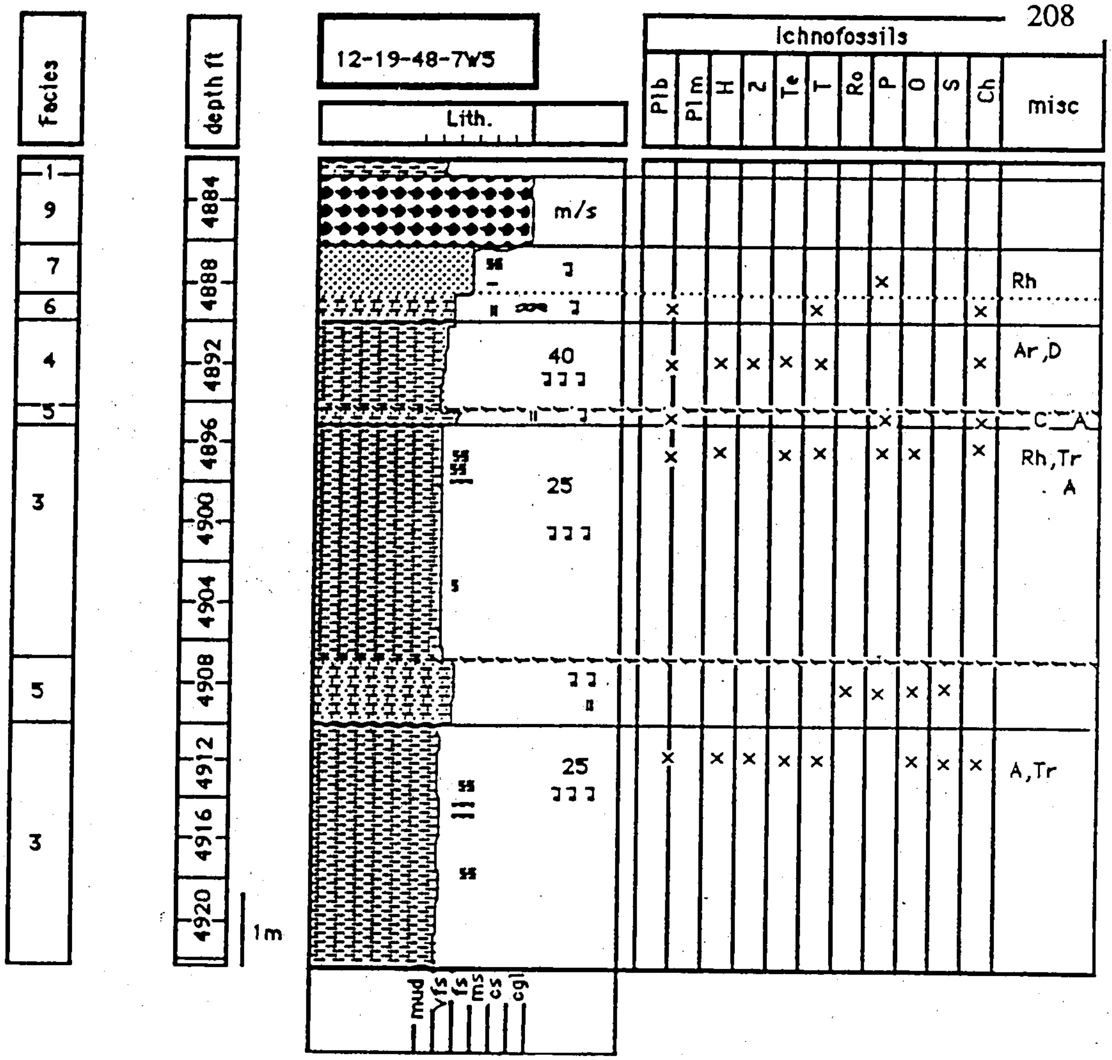
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Ch
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C A
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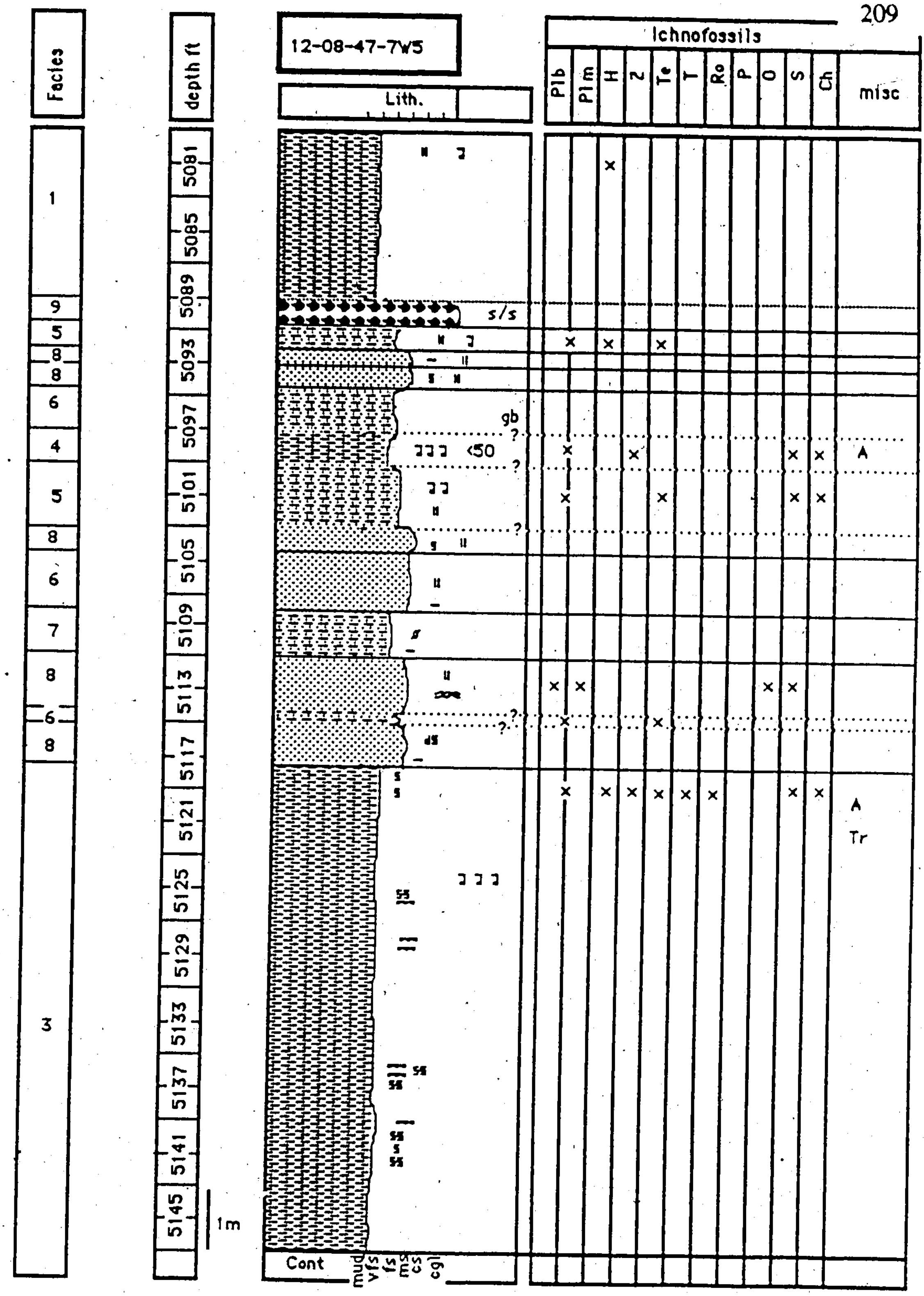
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Plm
H
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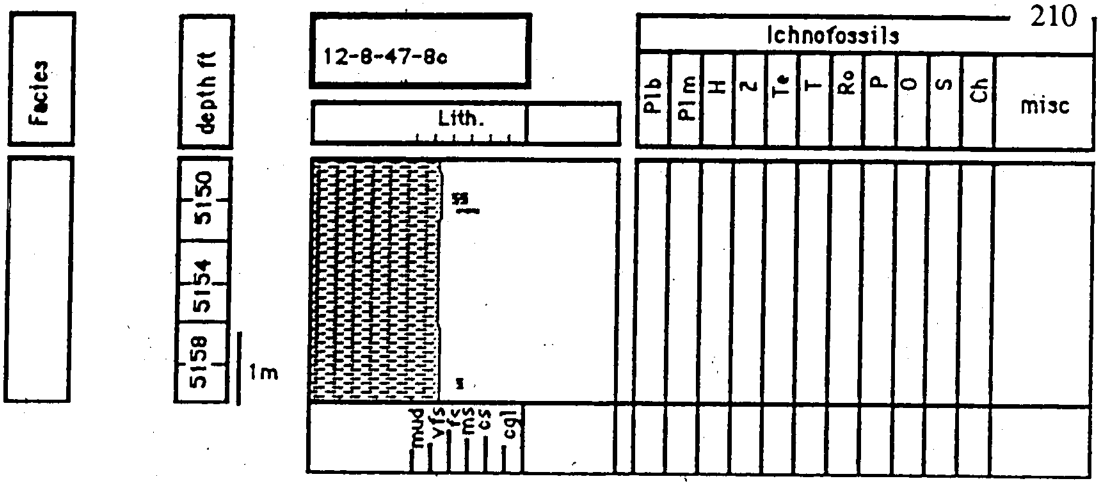
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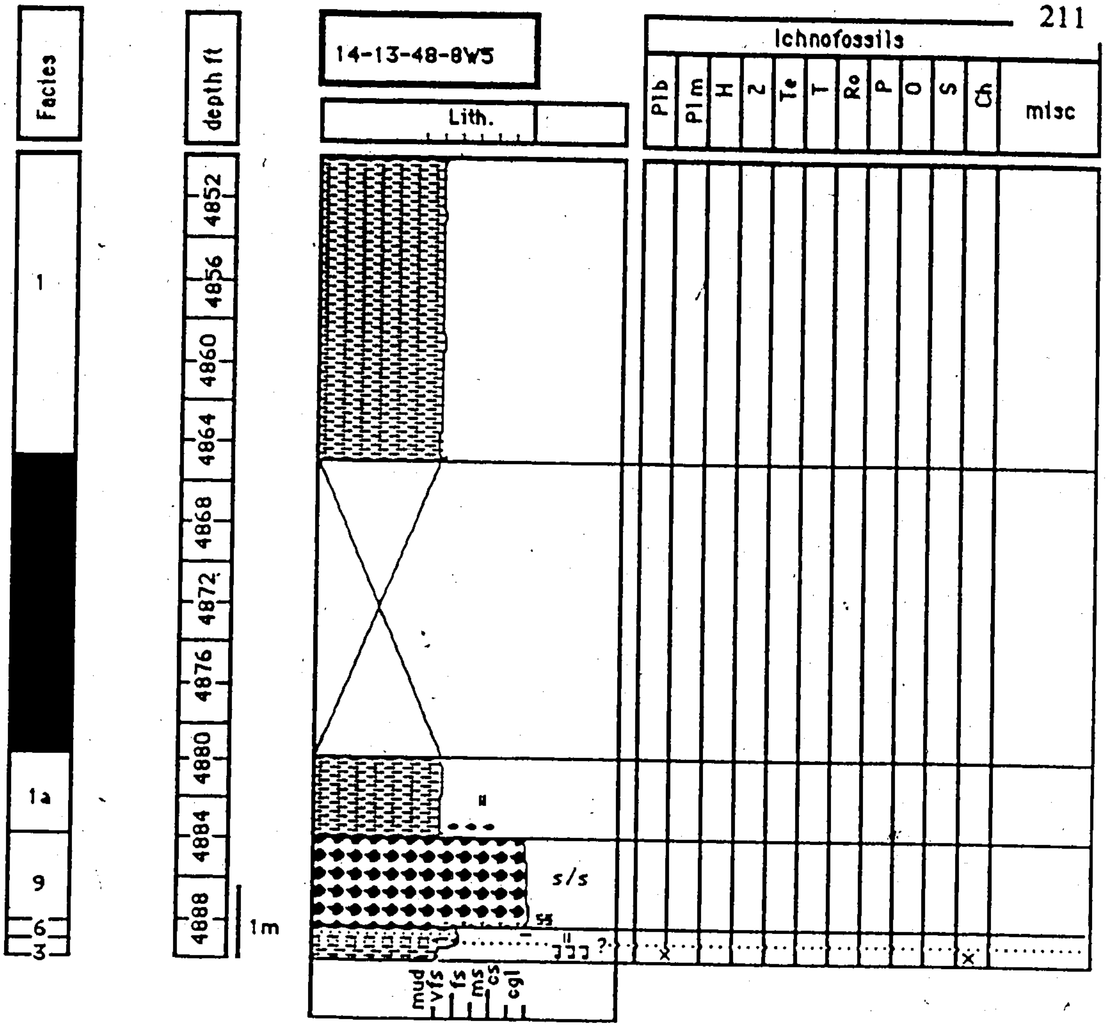
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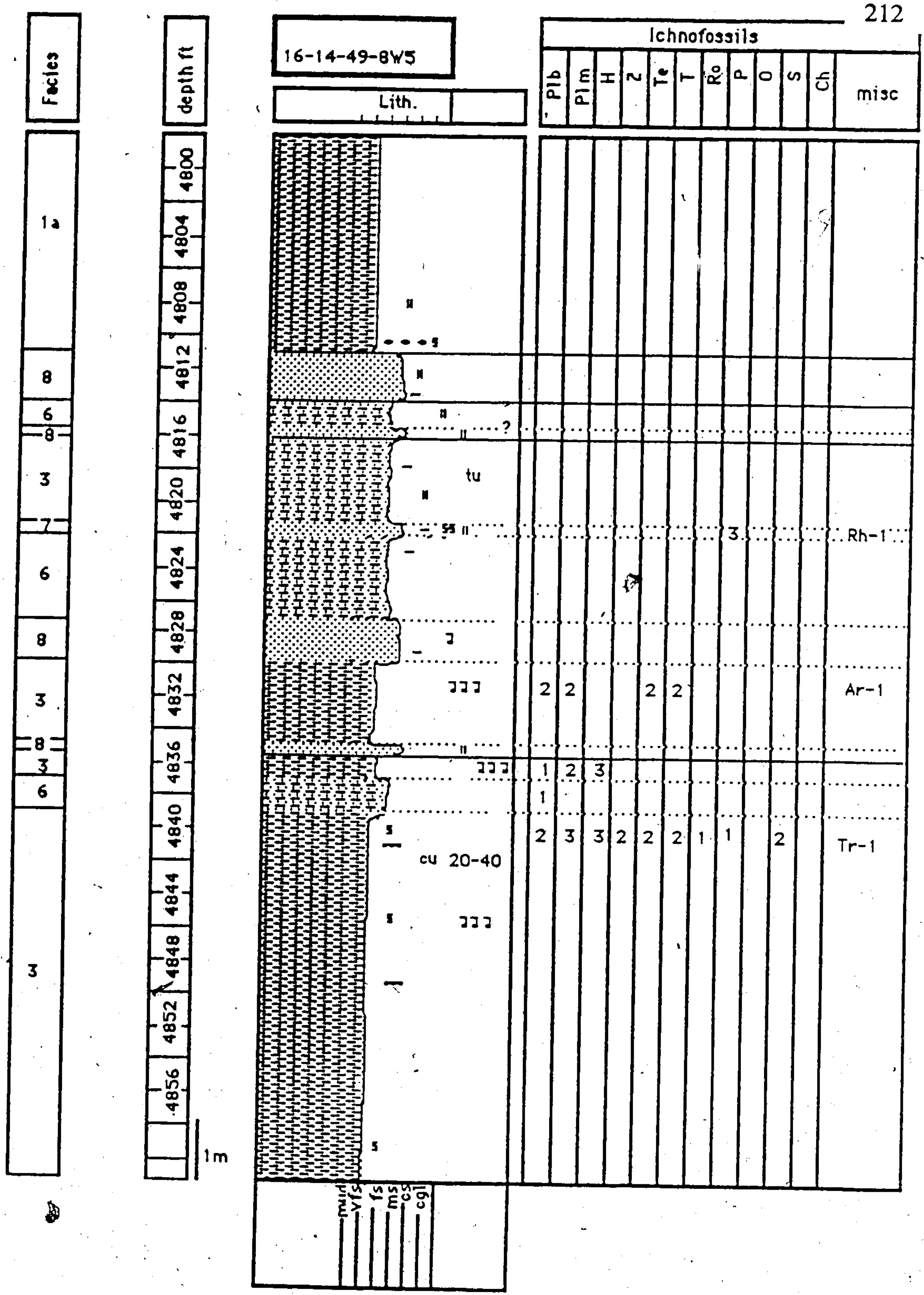
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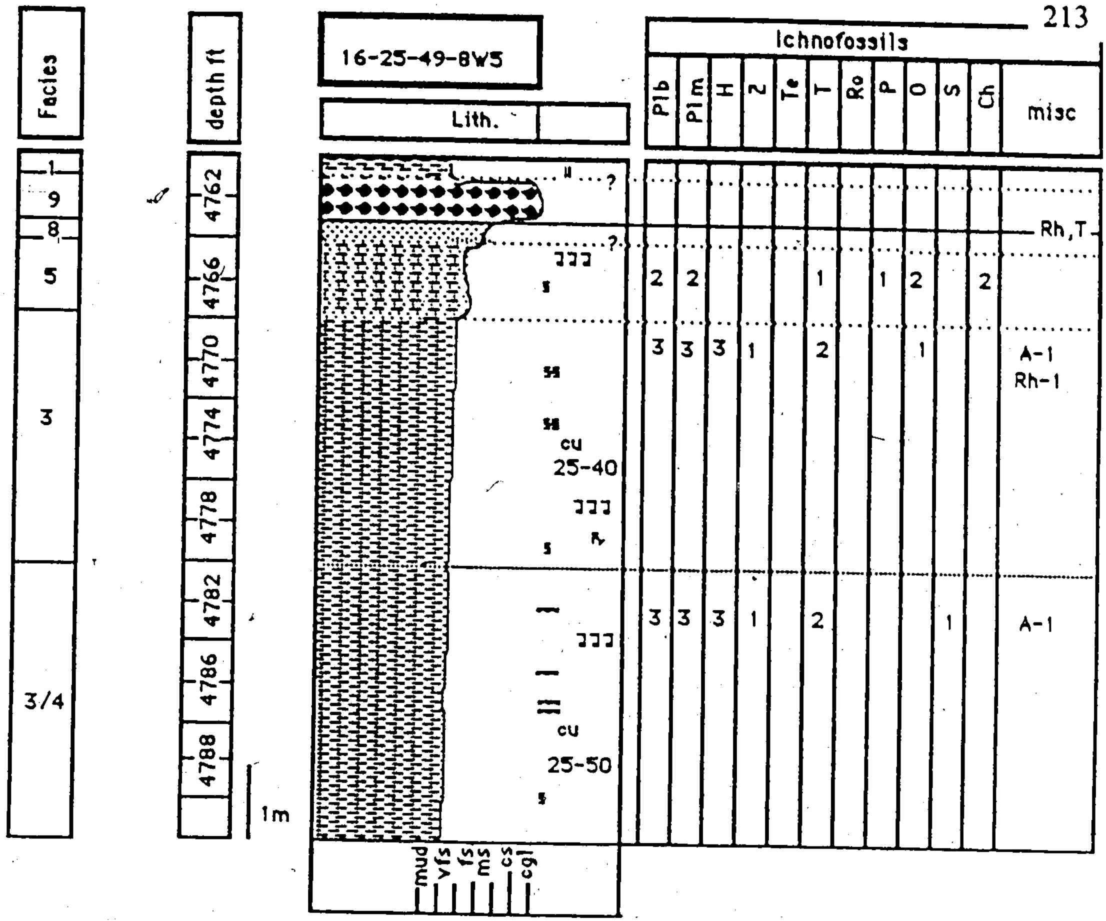
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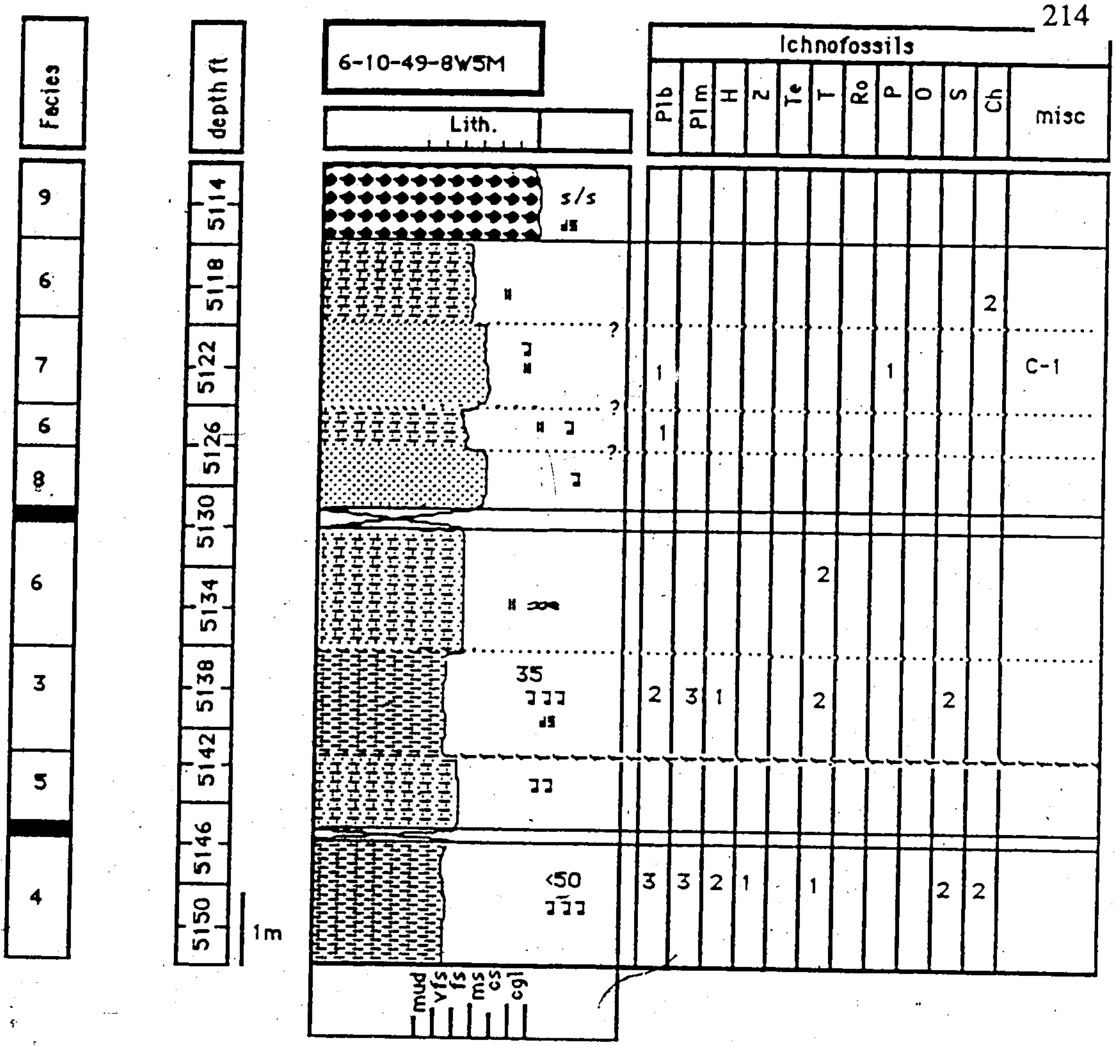
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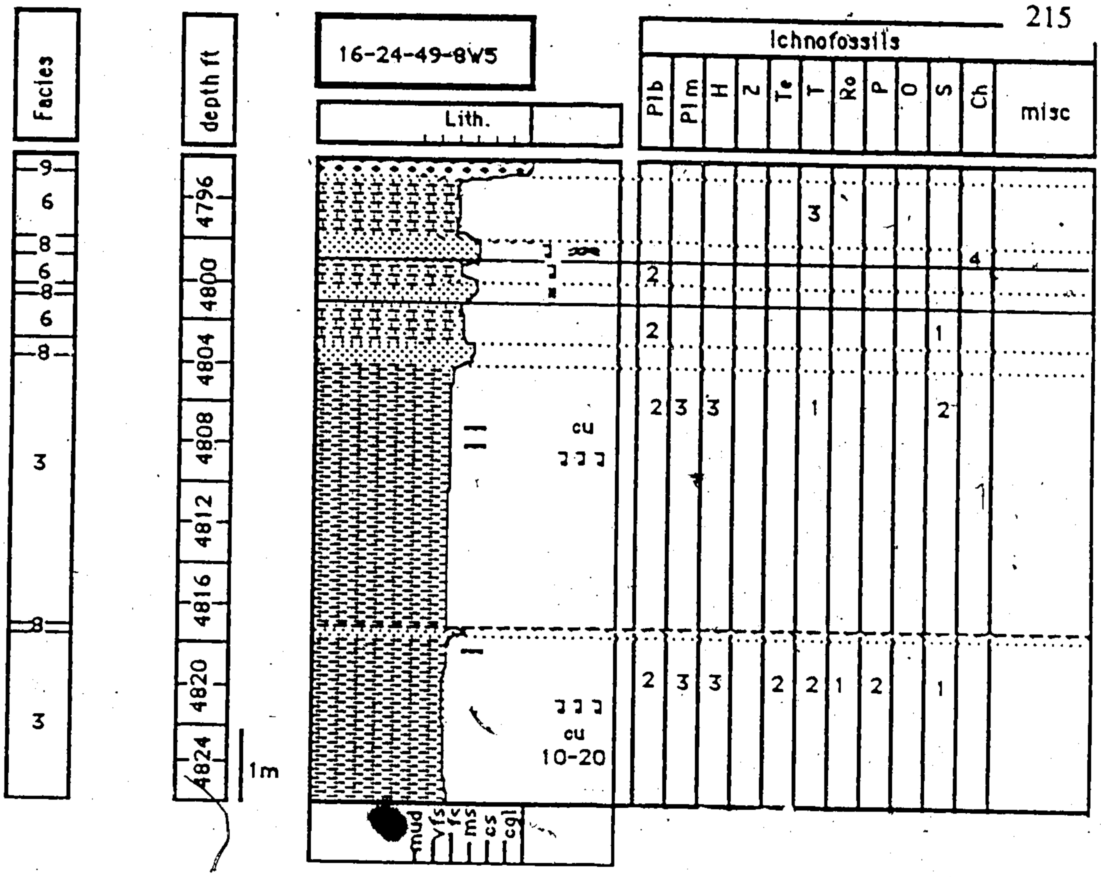
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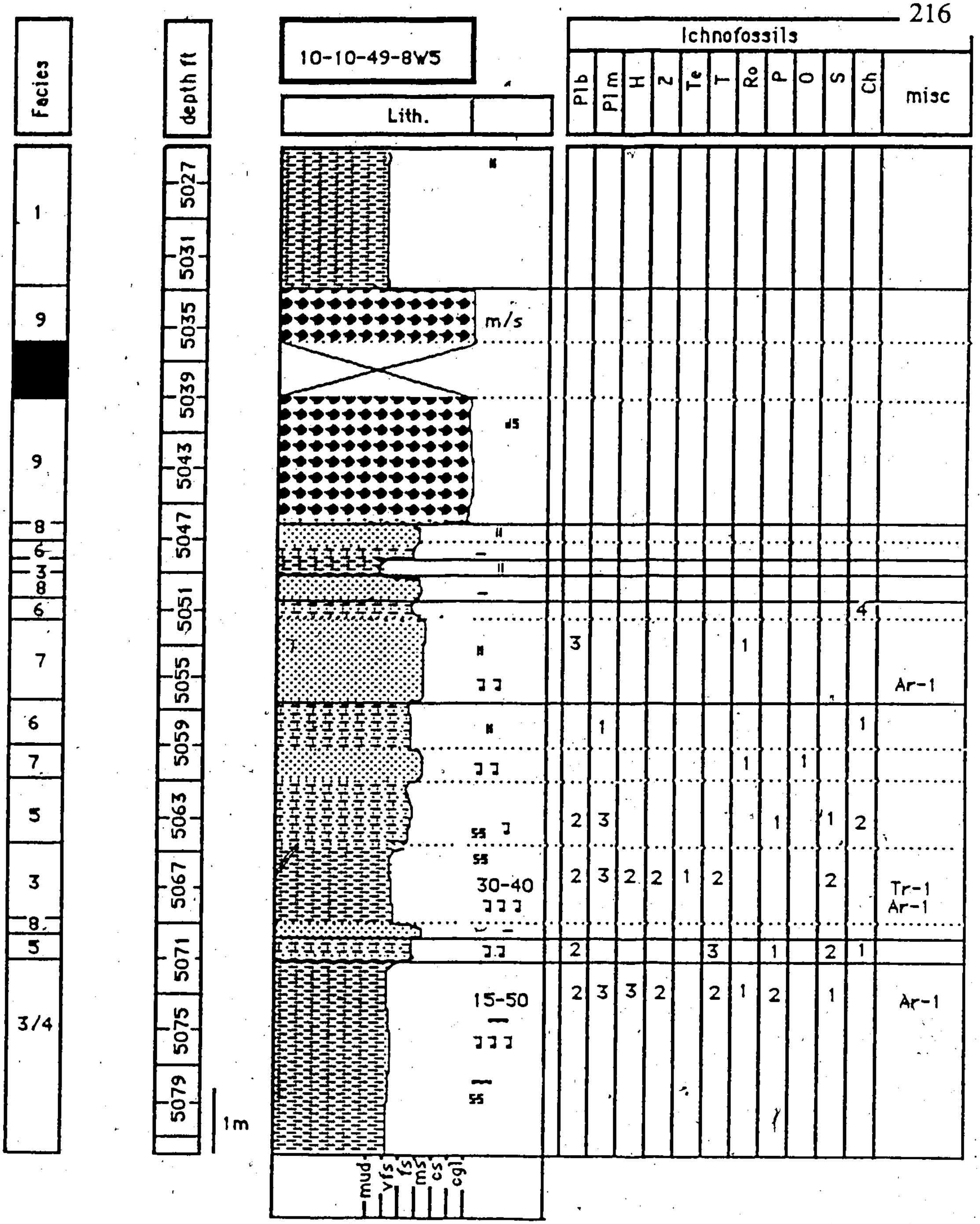
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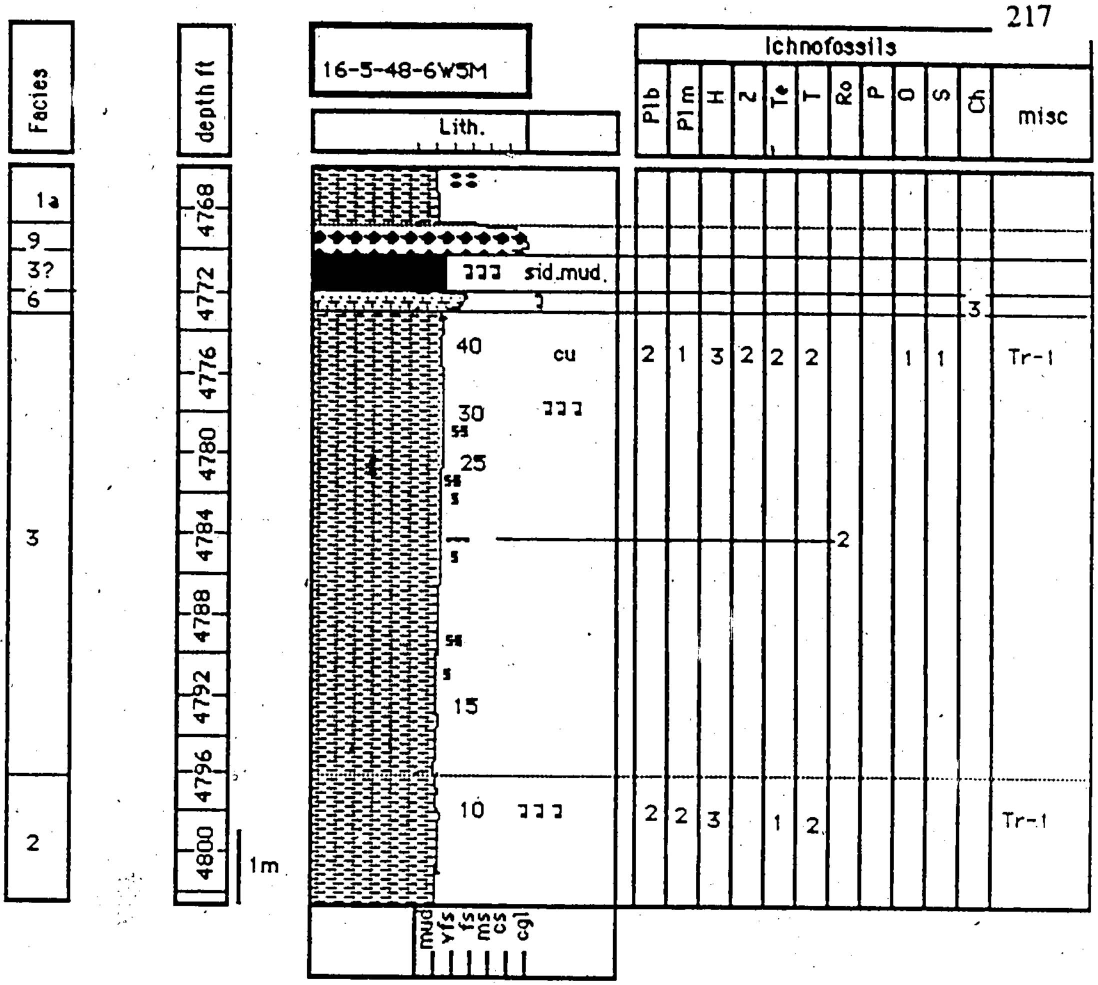
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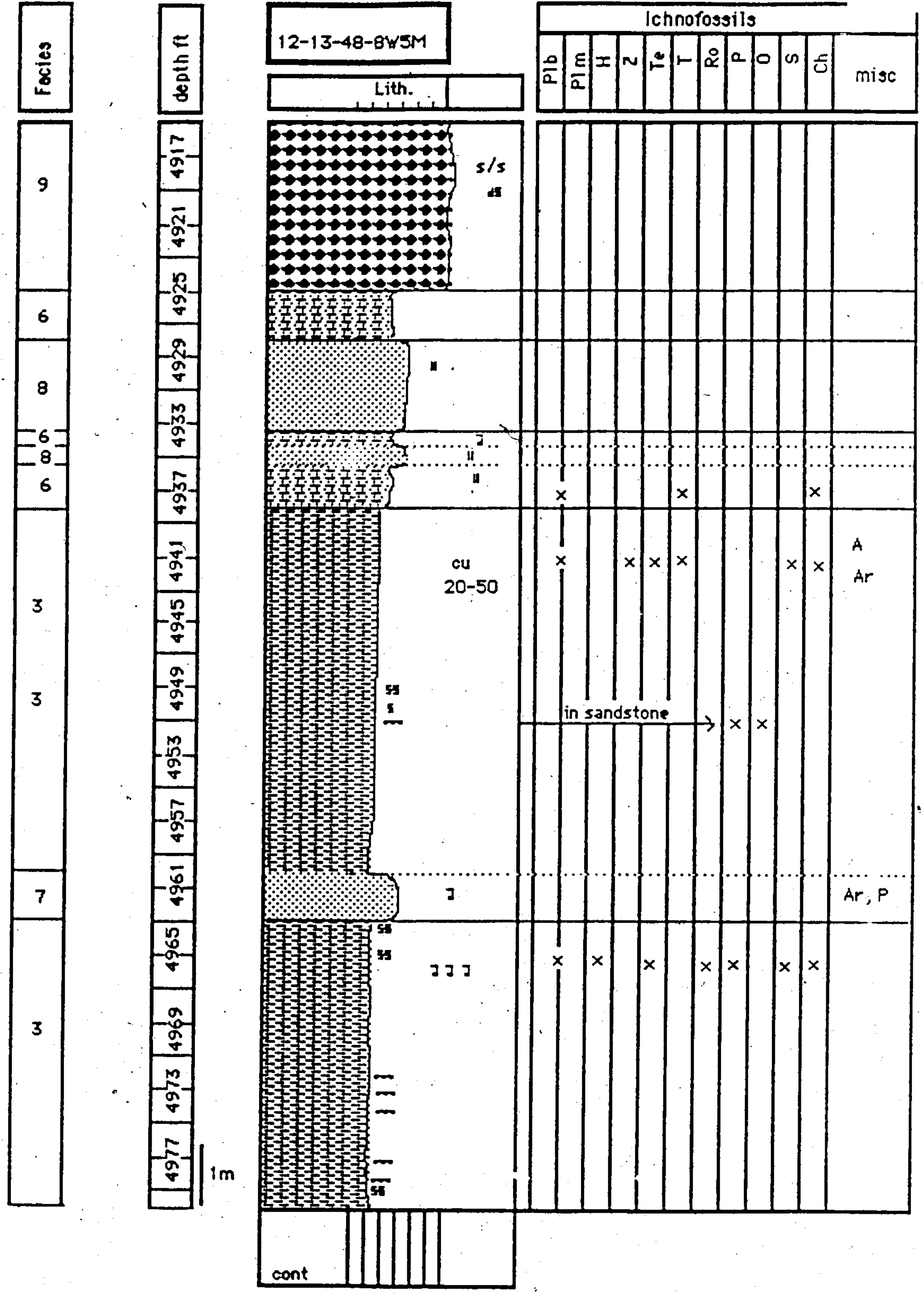
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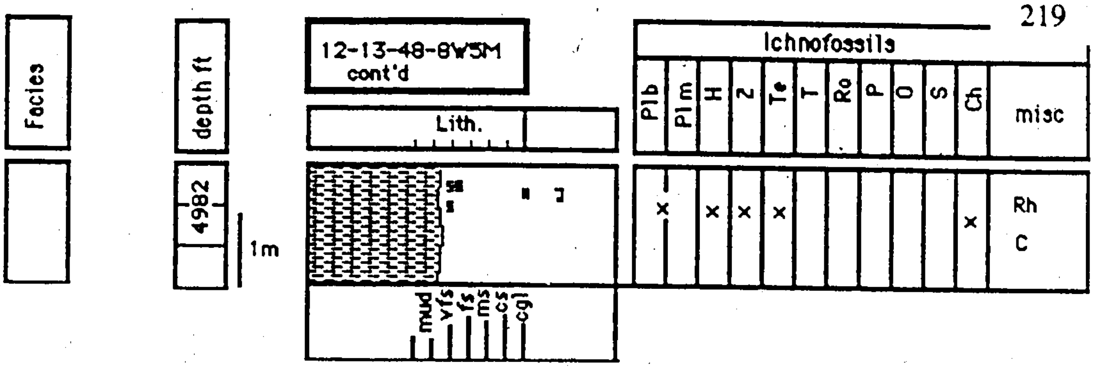
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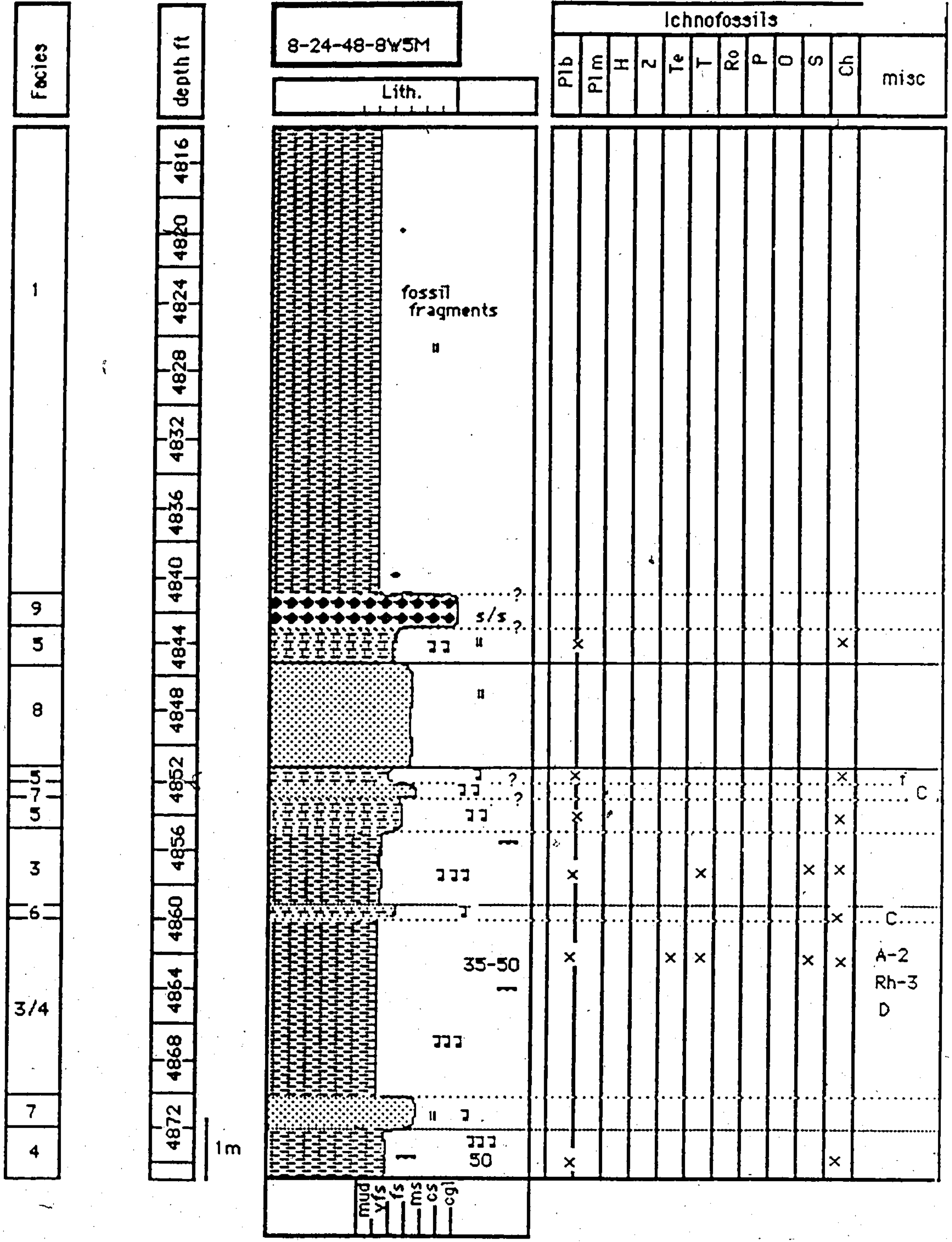
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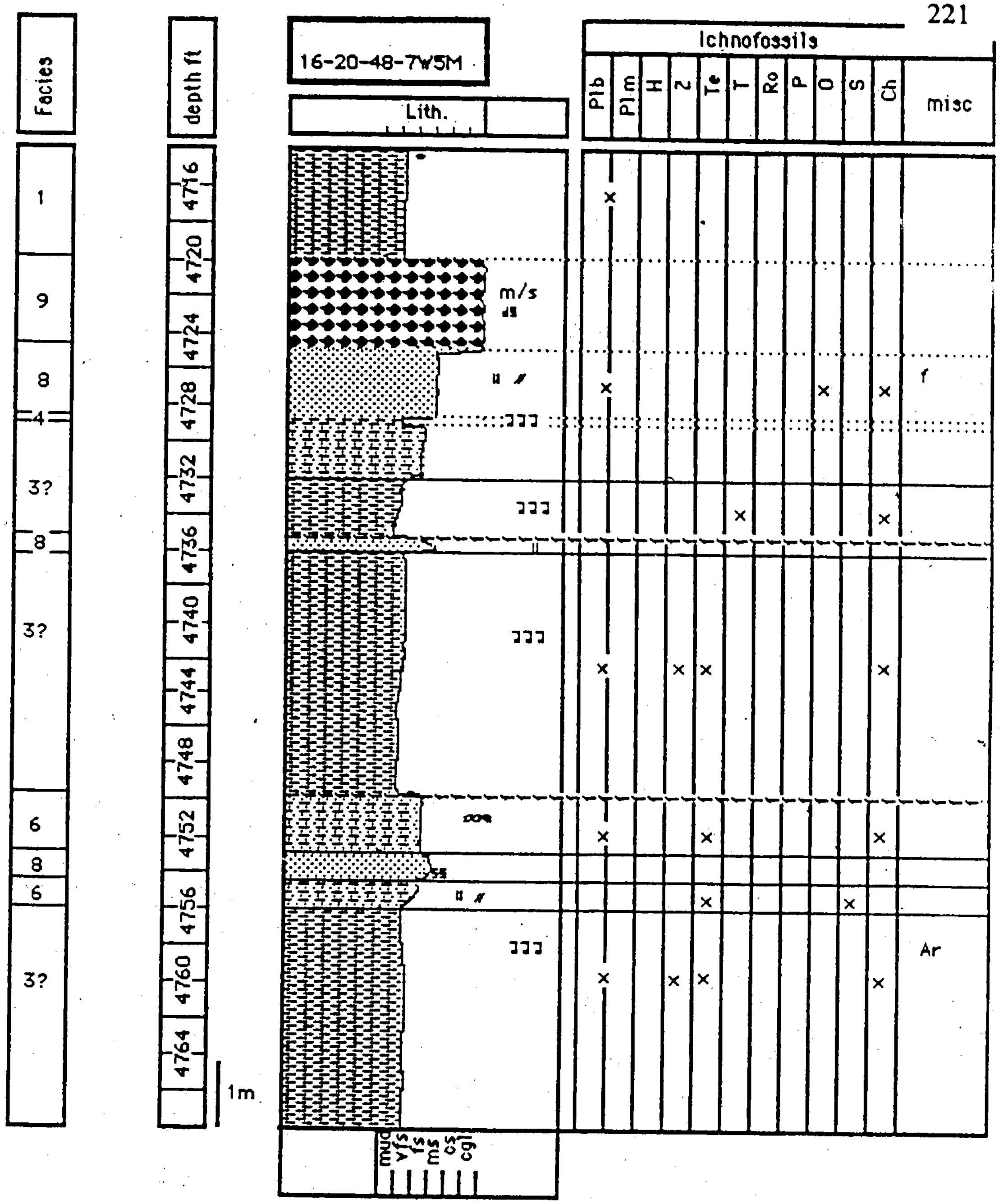
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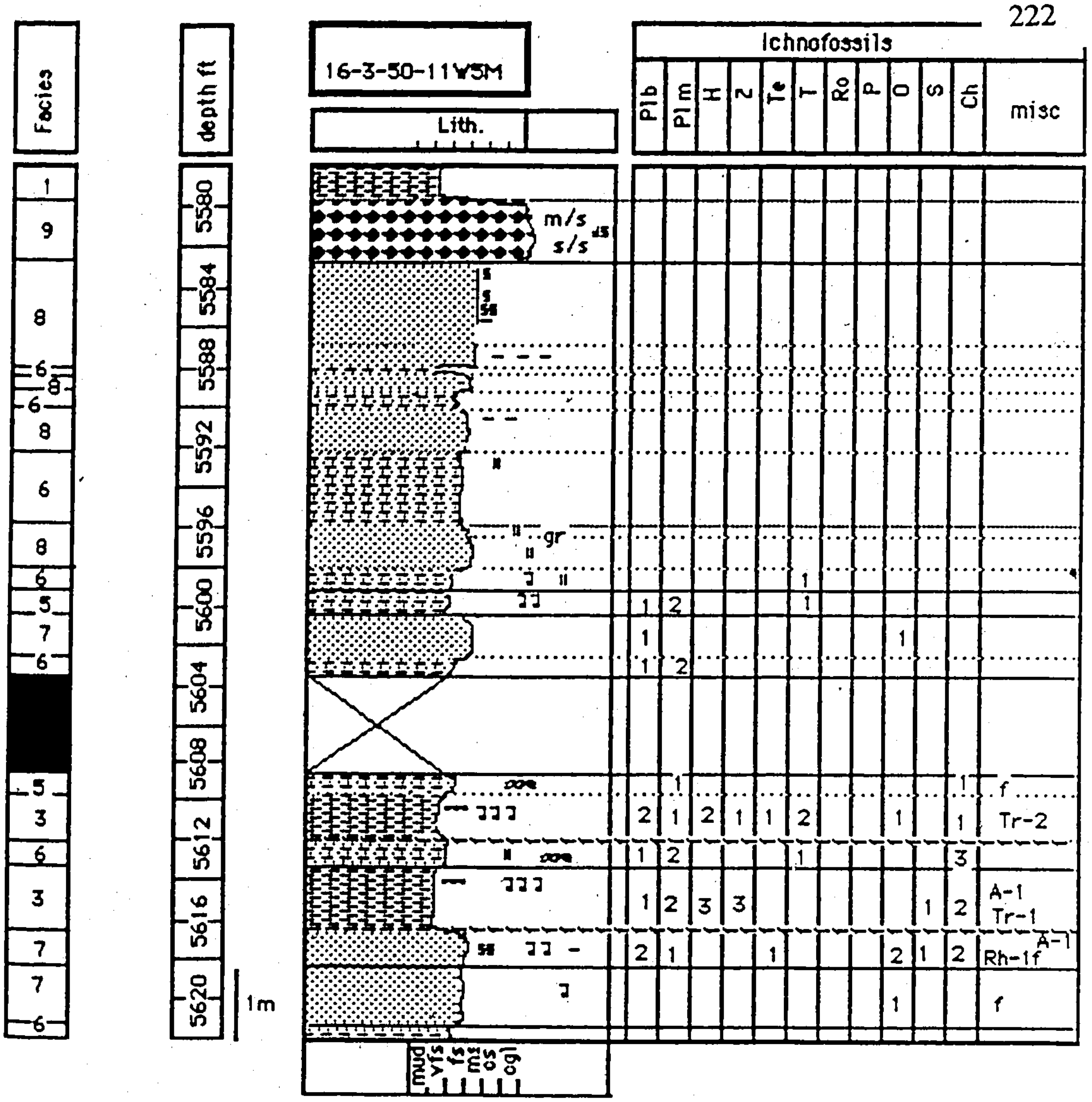
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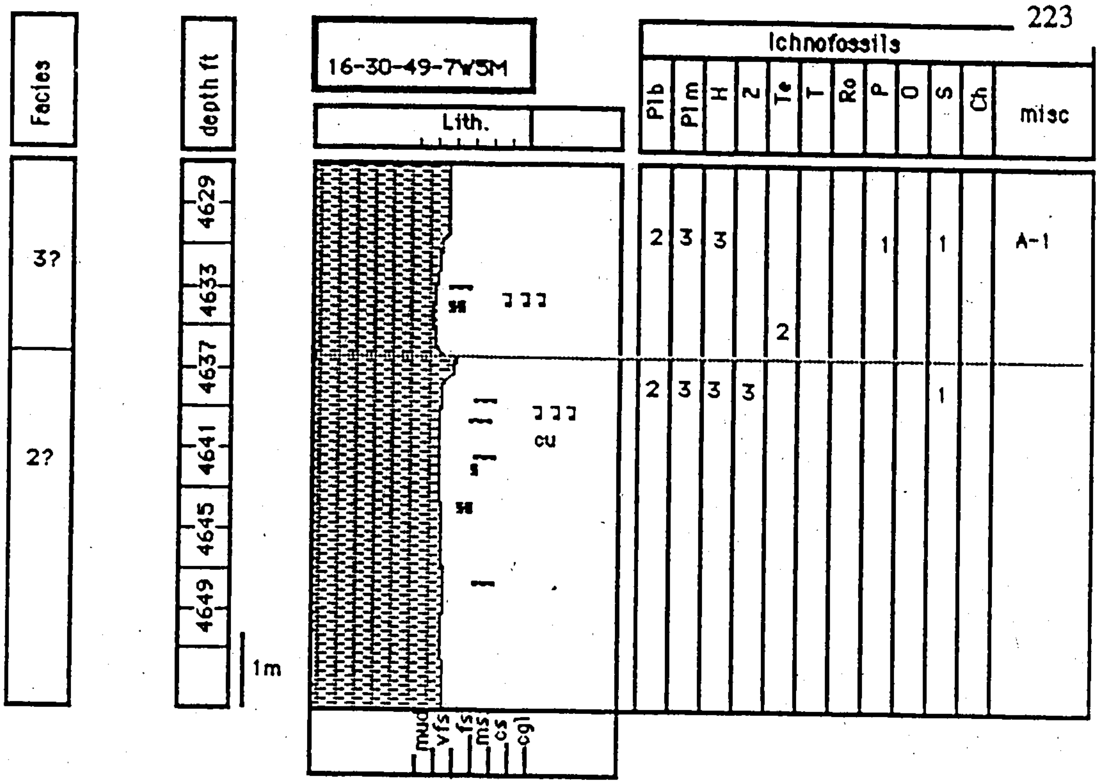
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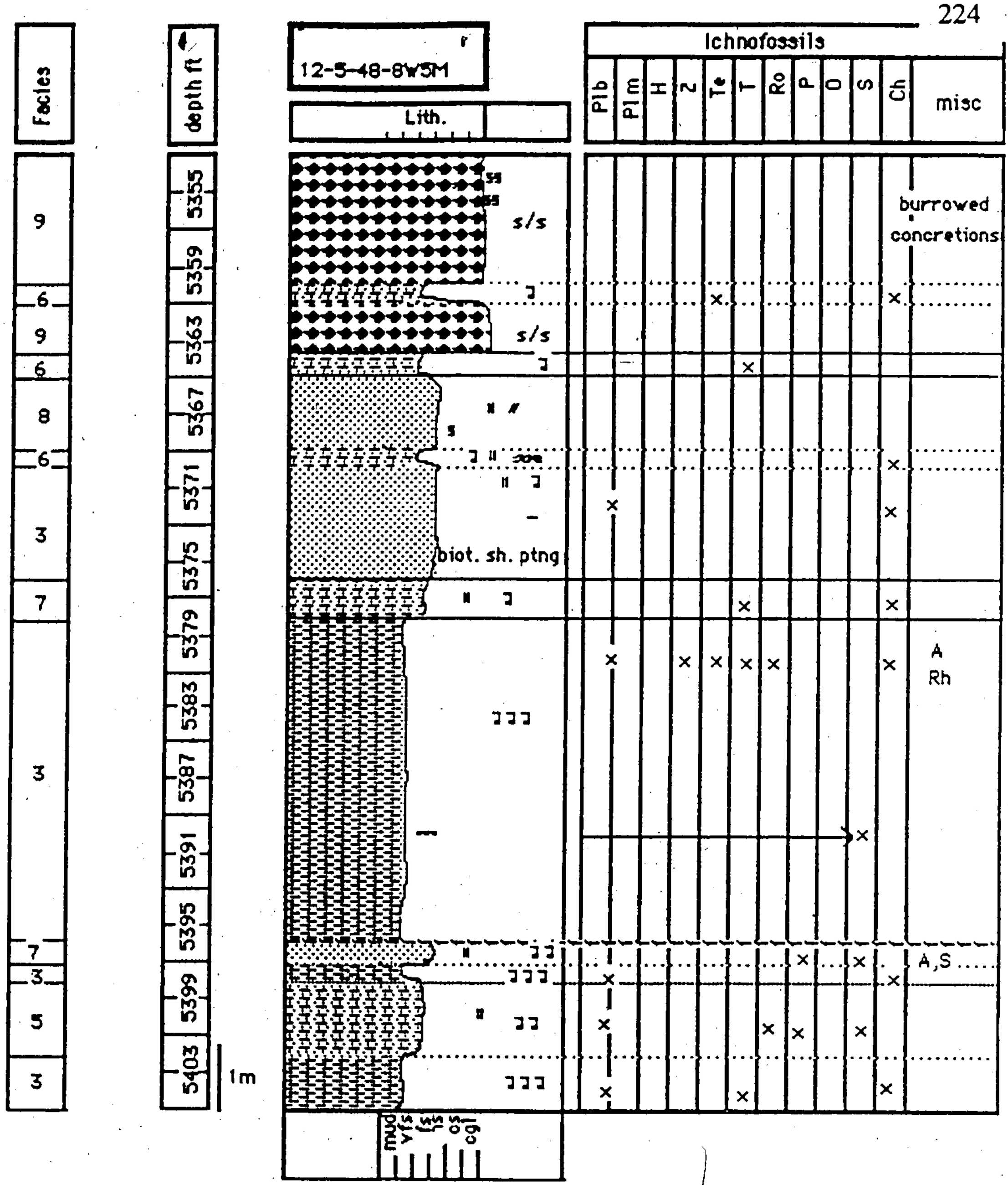
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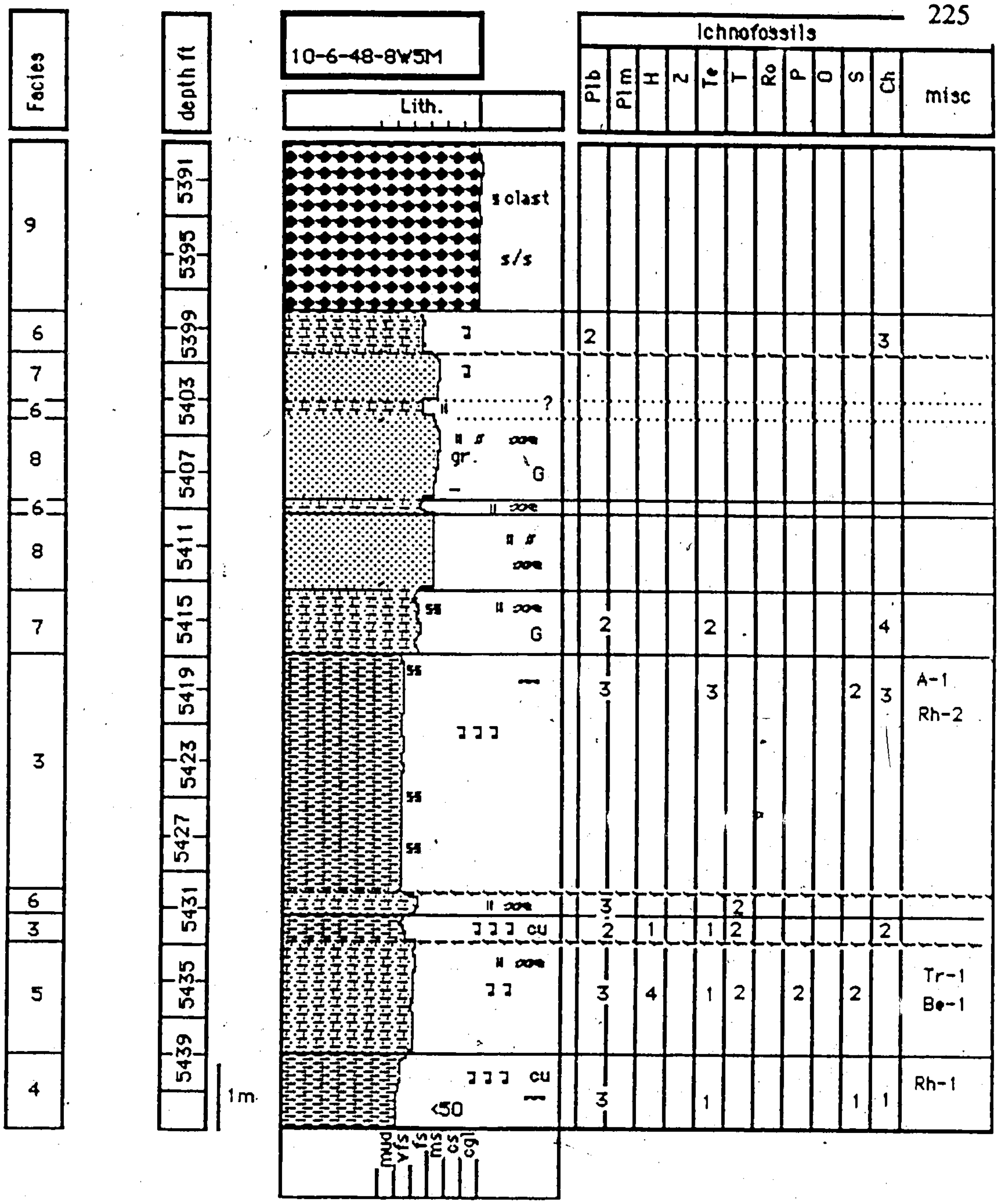
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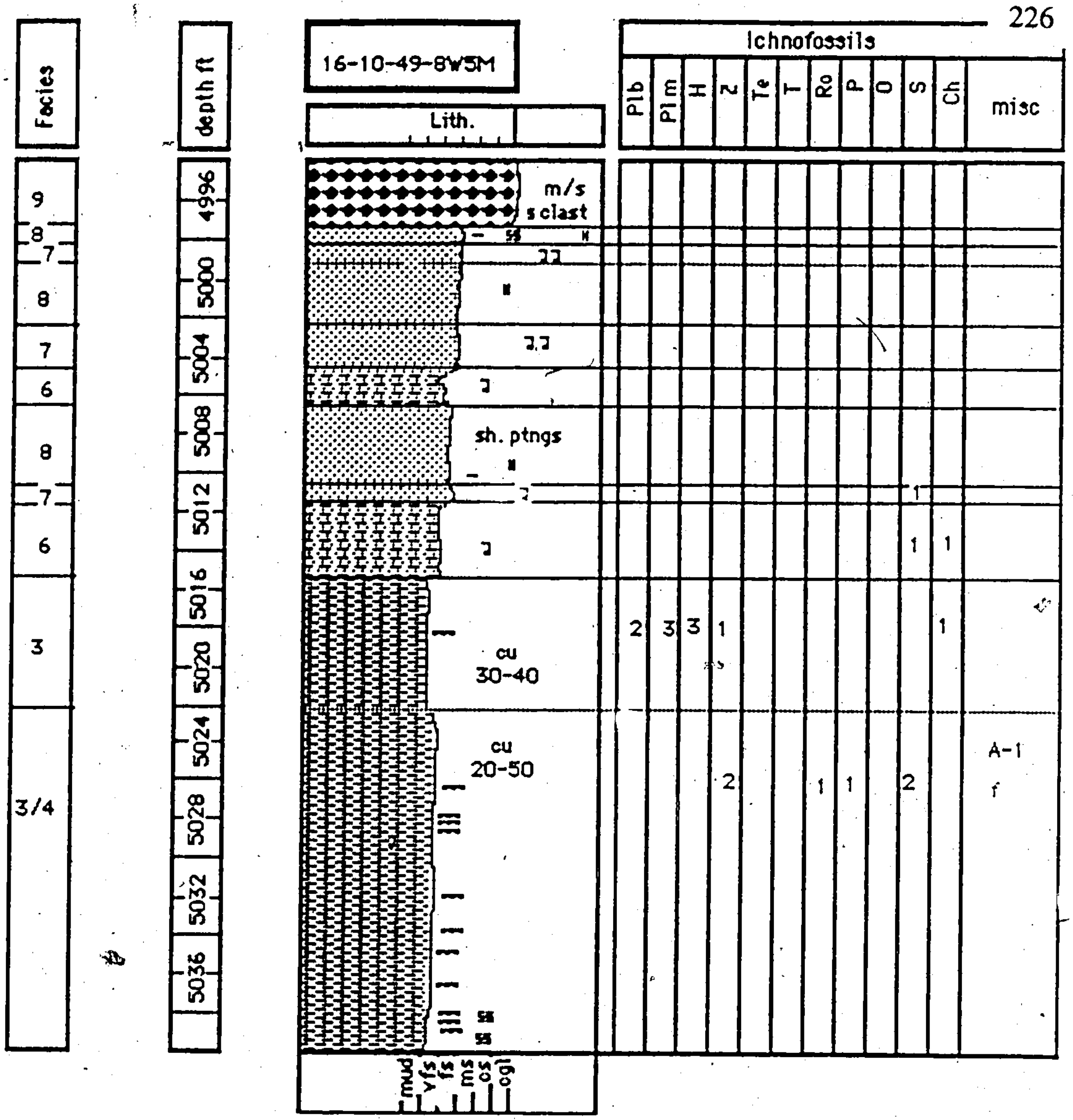
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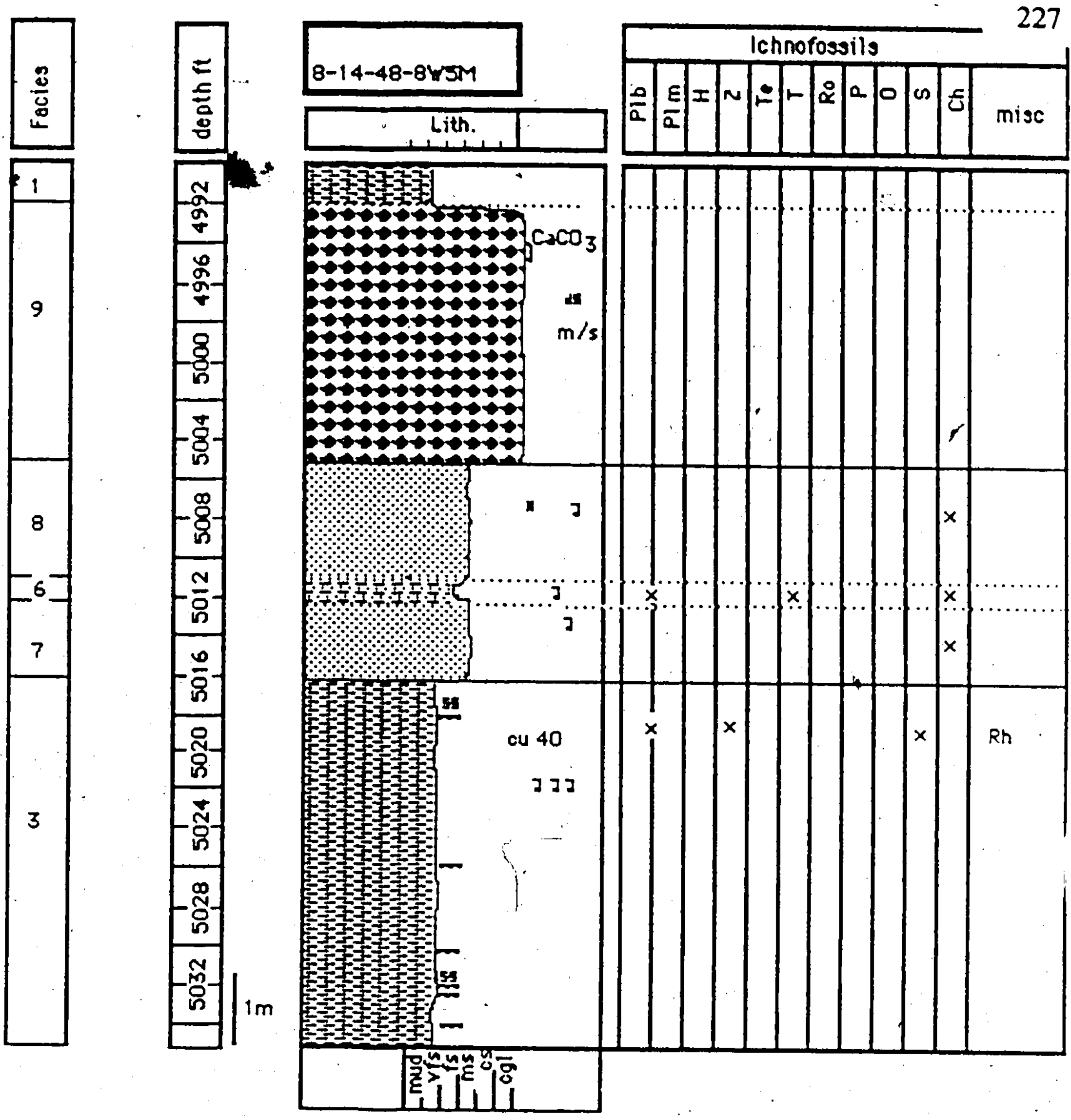
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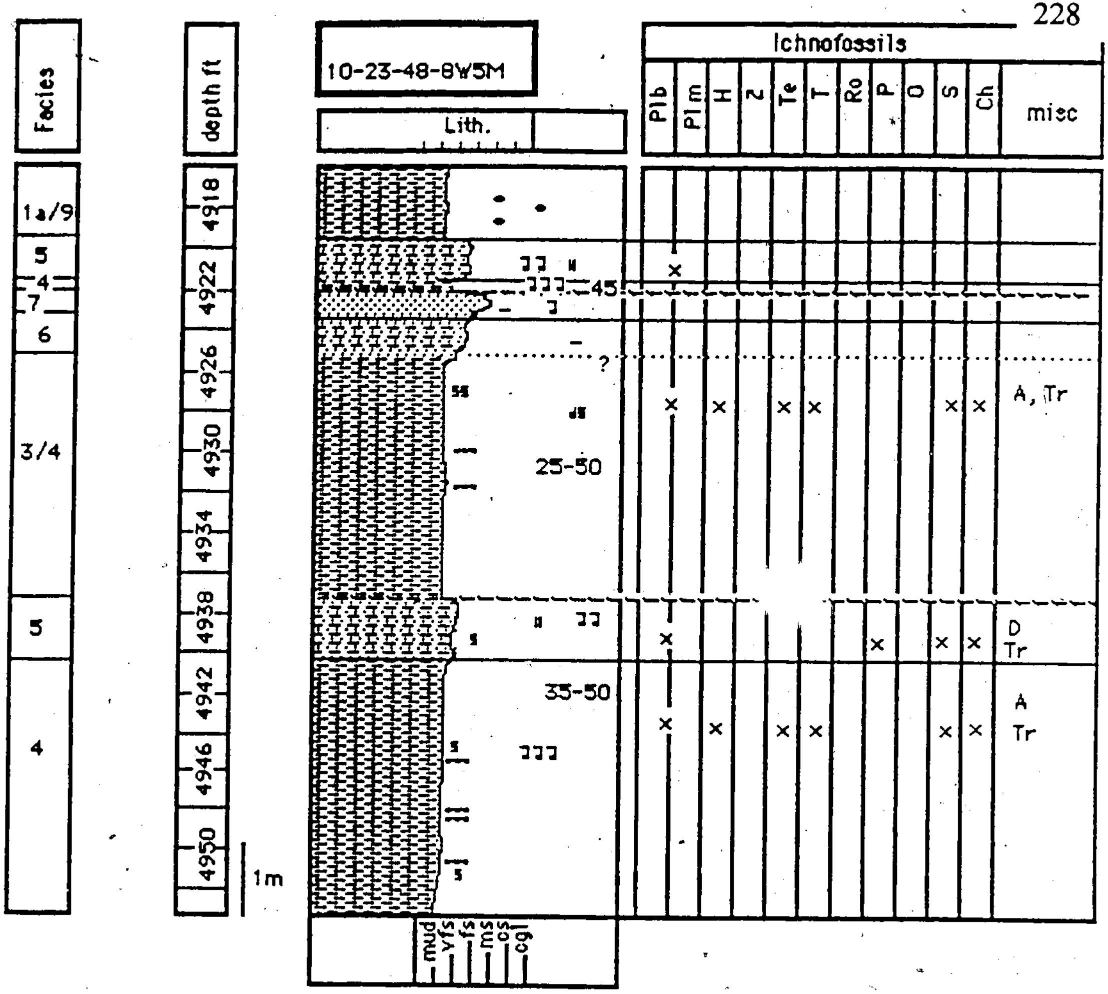
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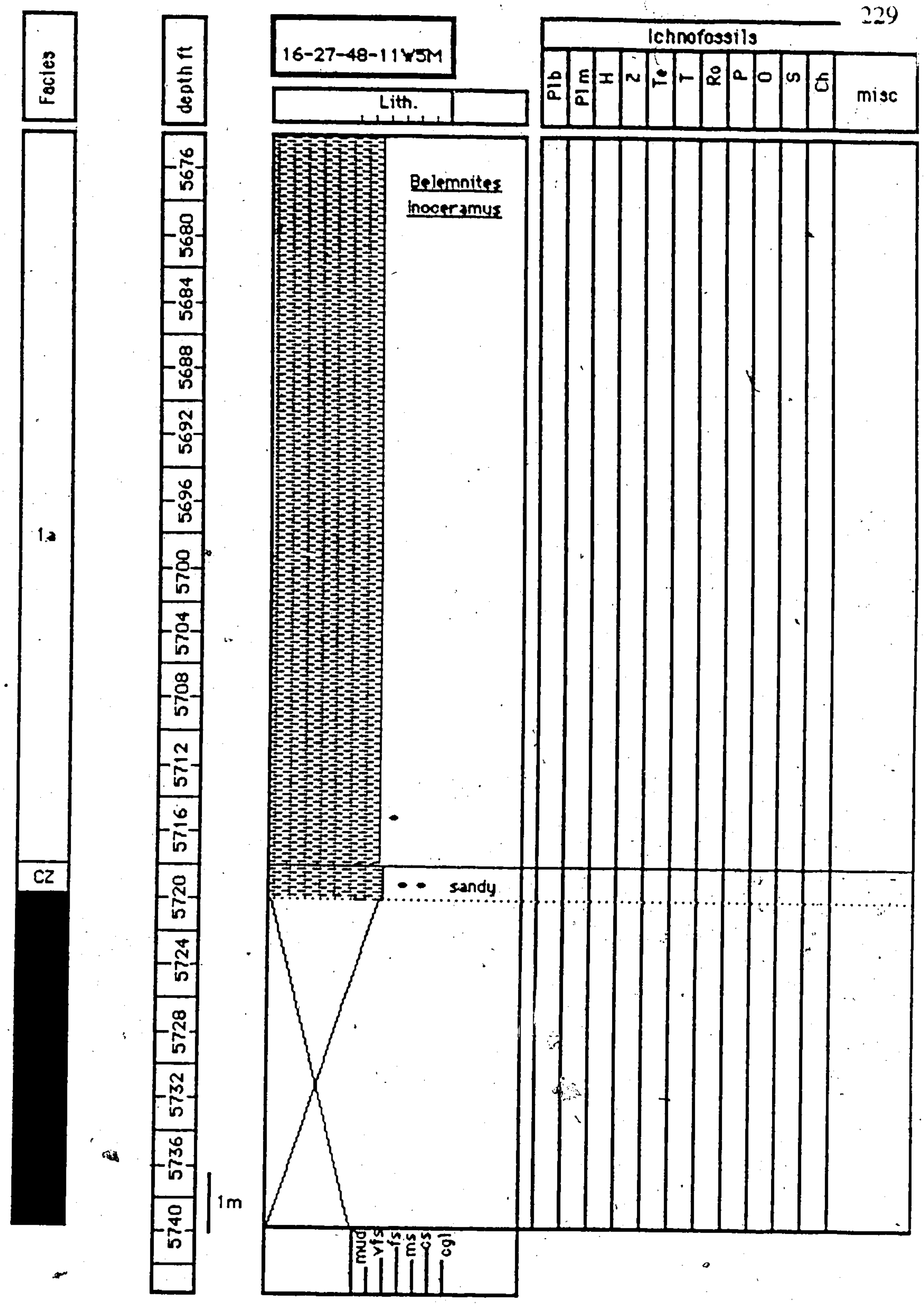
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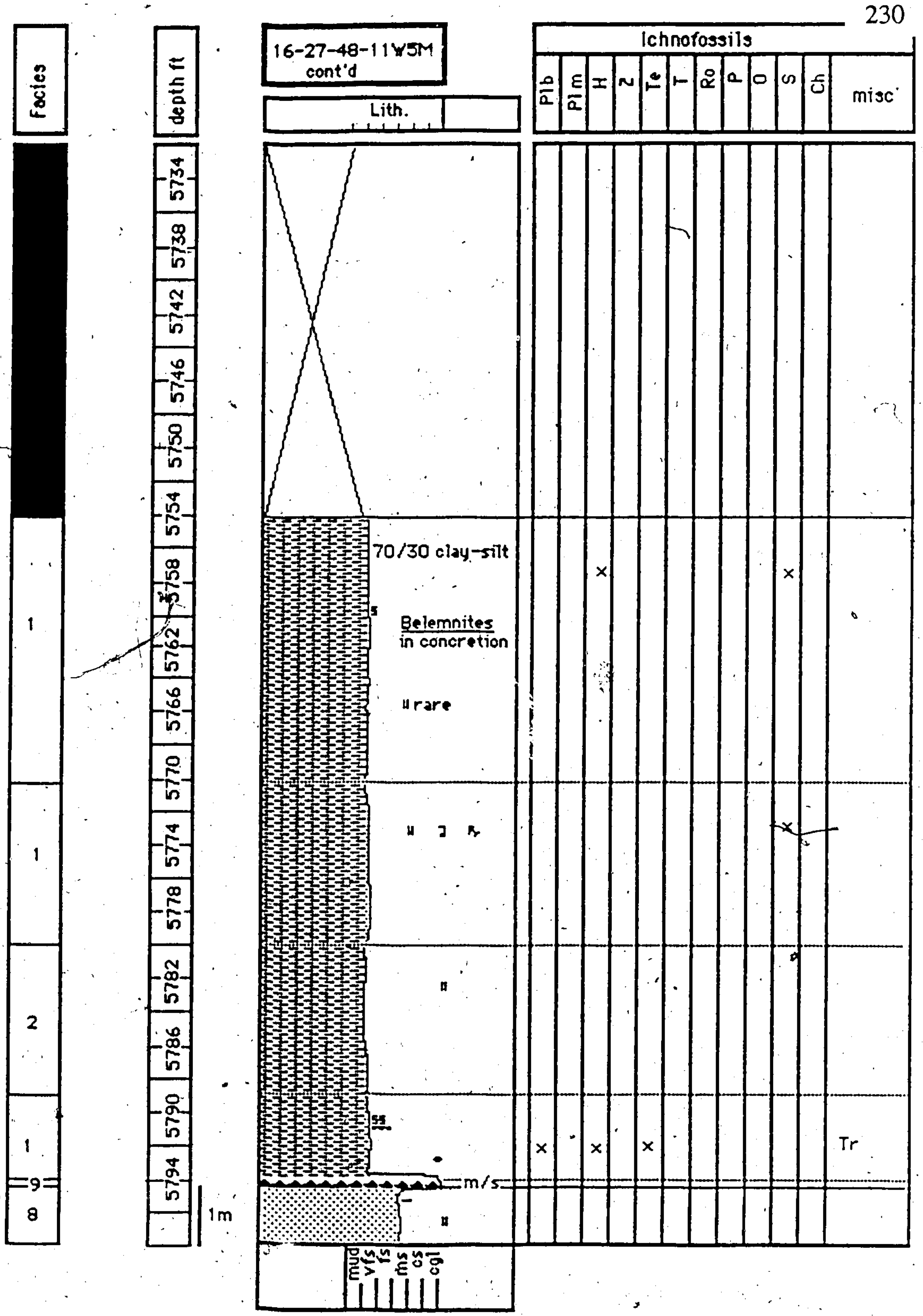
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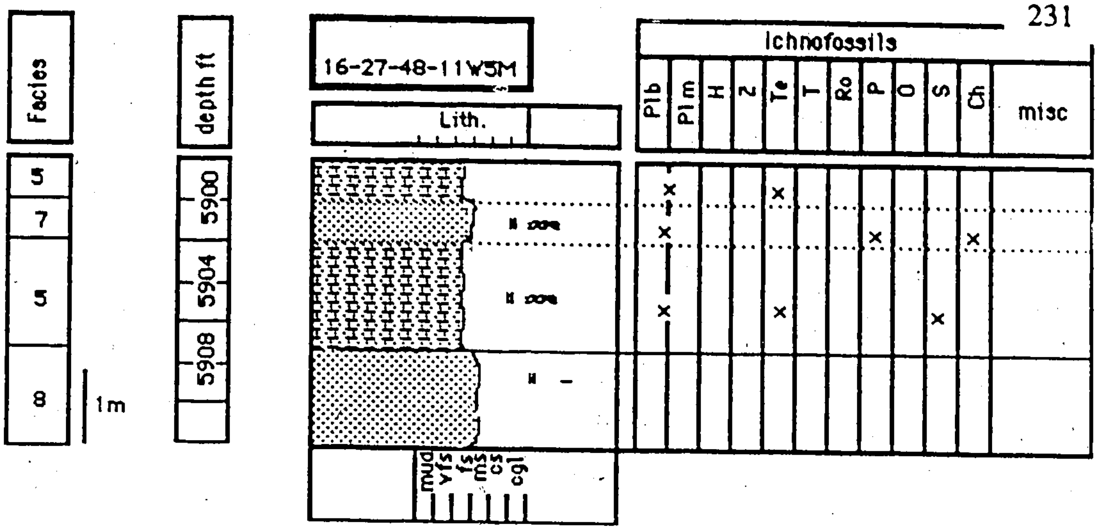
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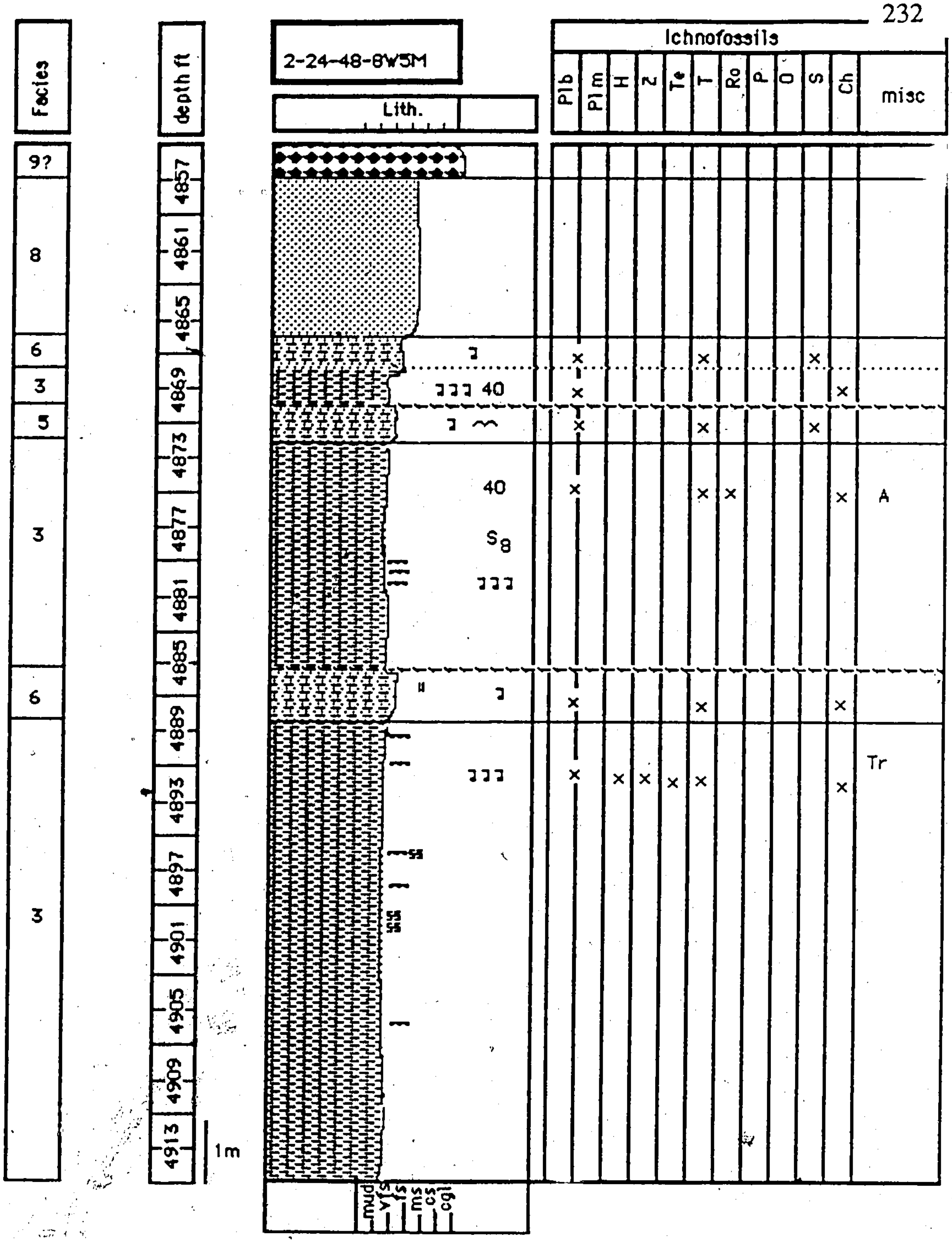
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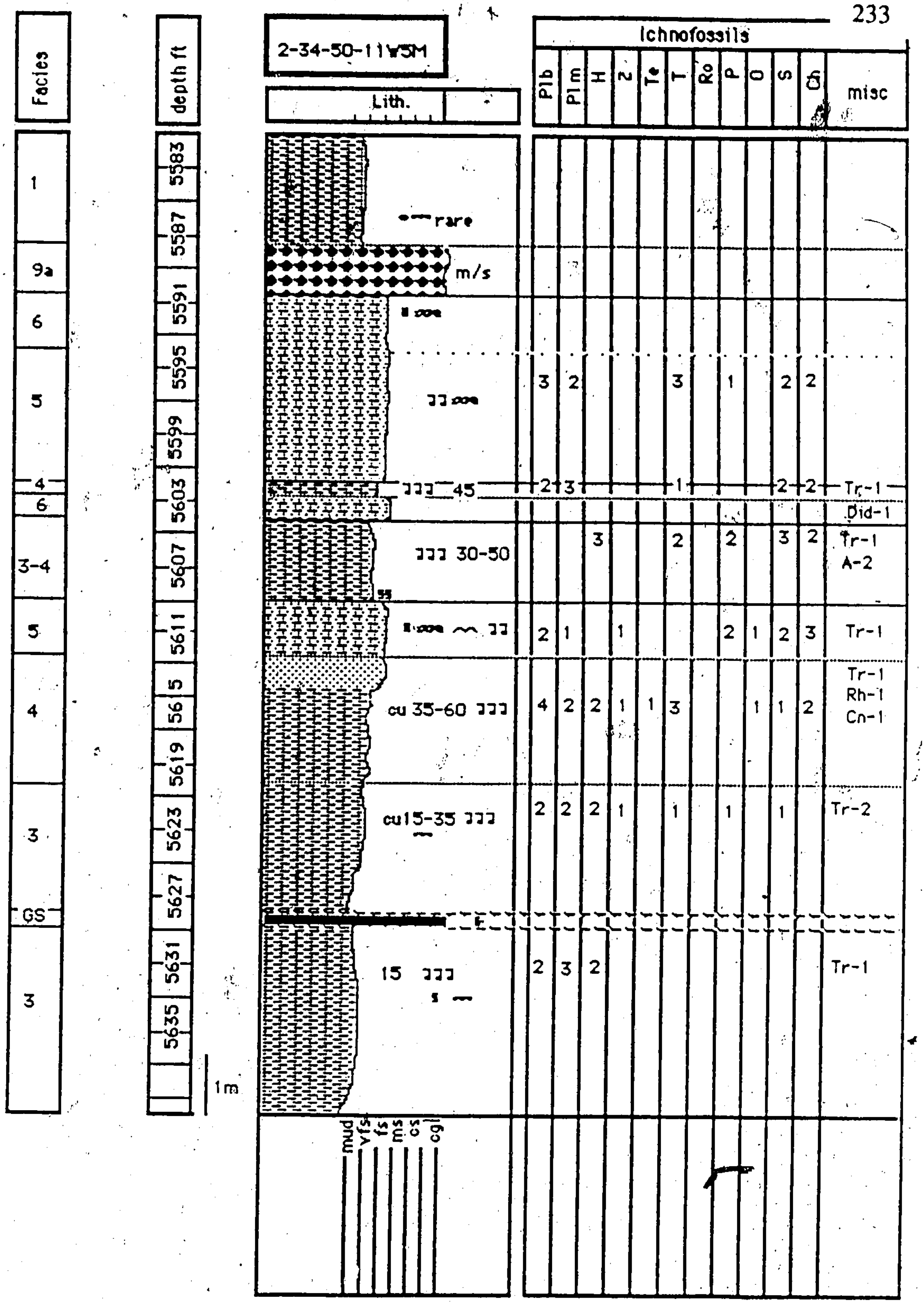
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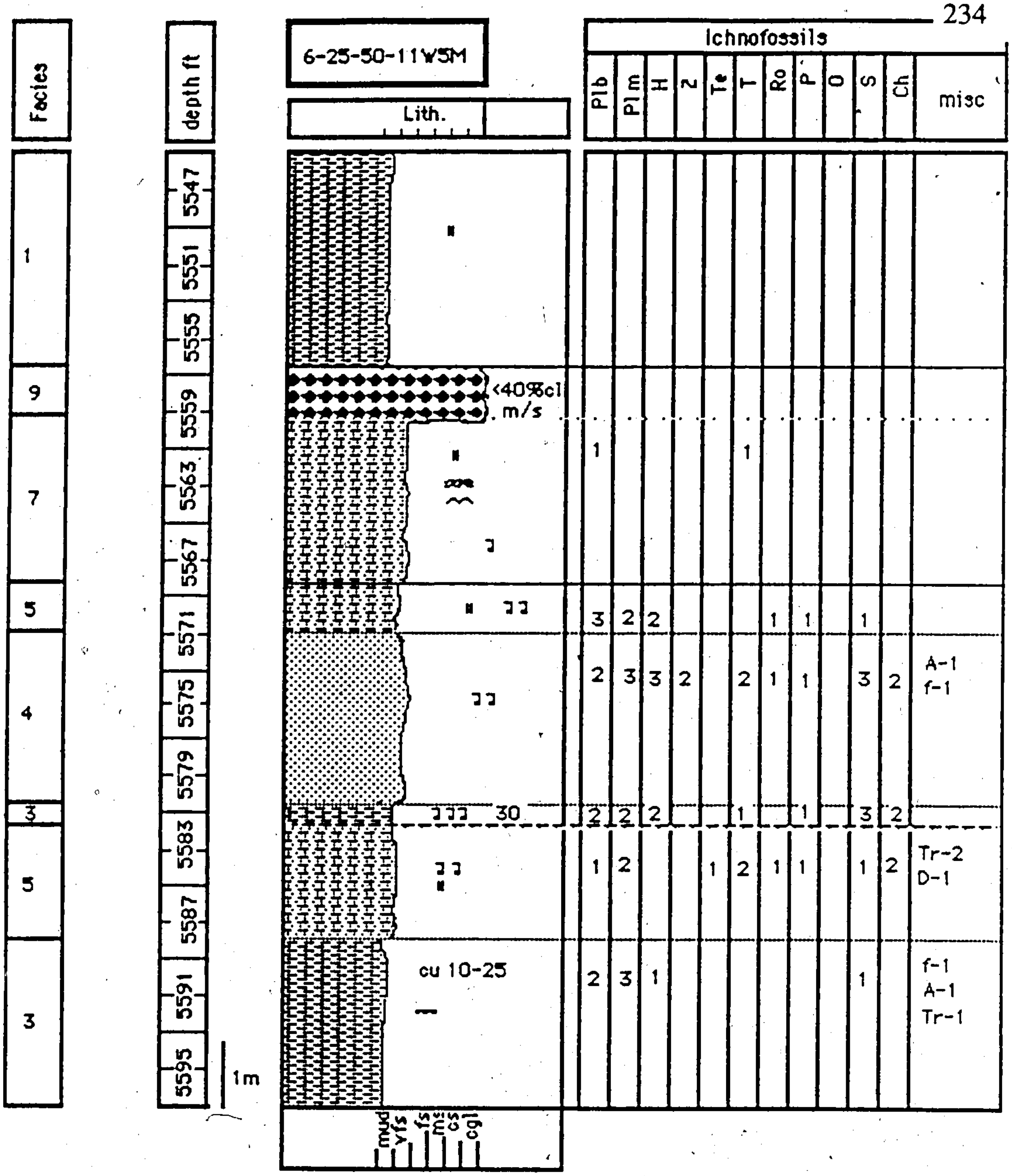
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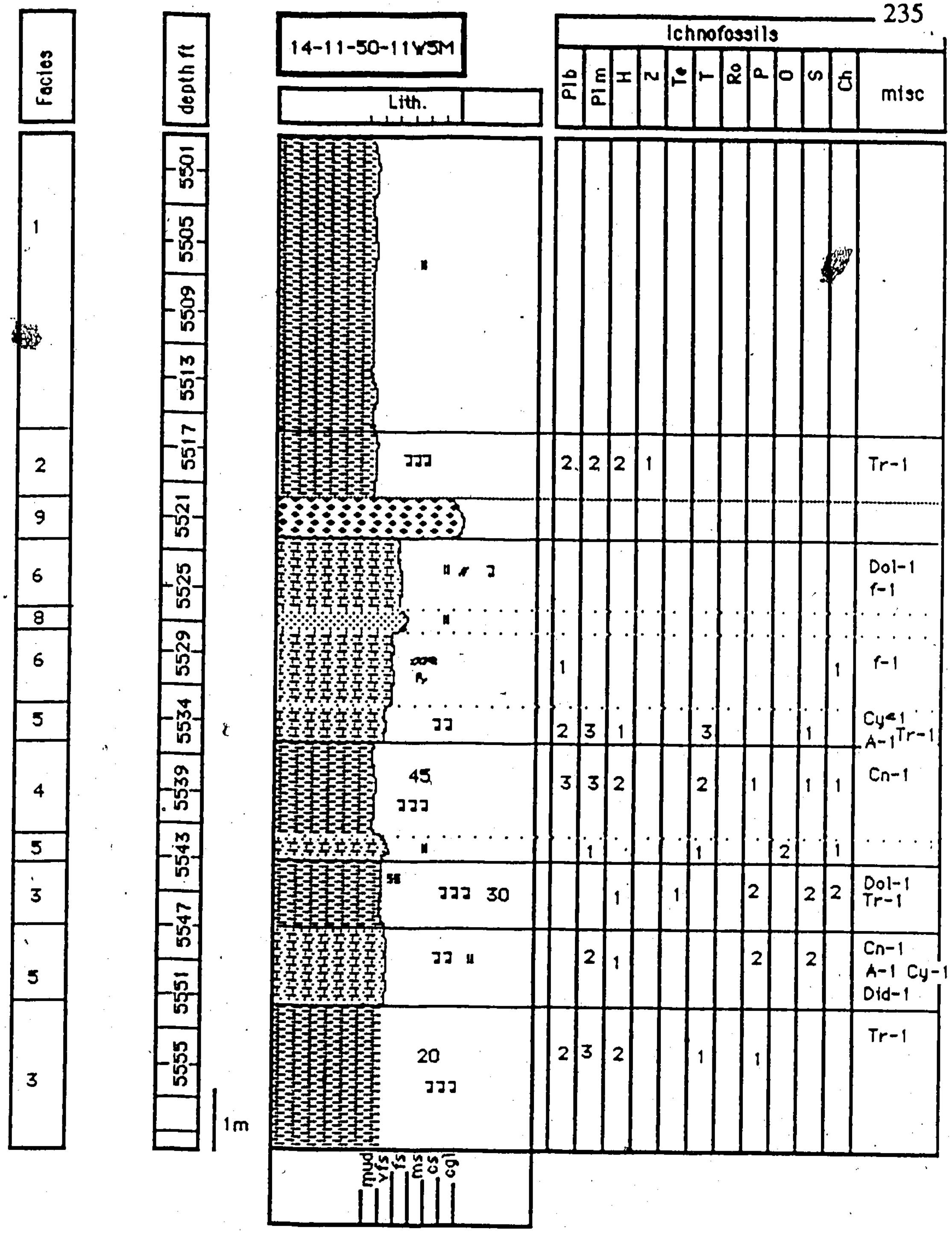
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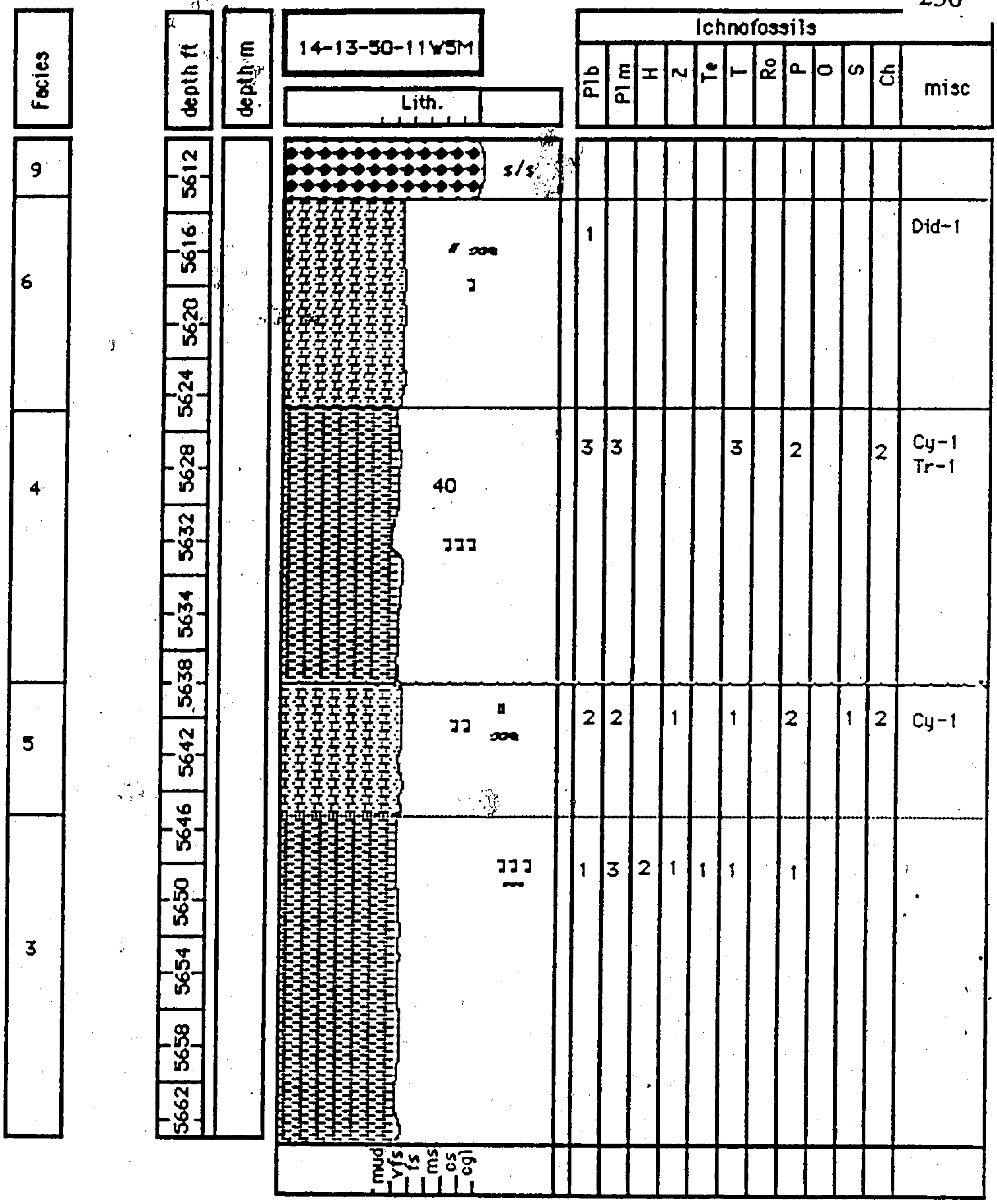
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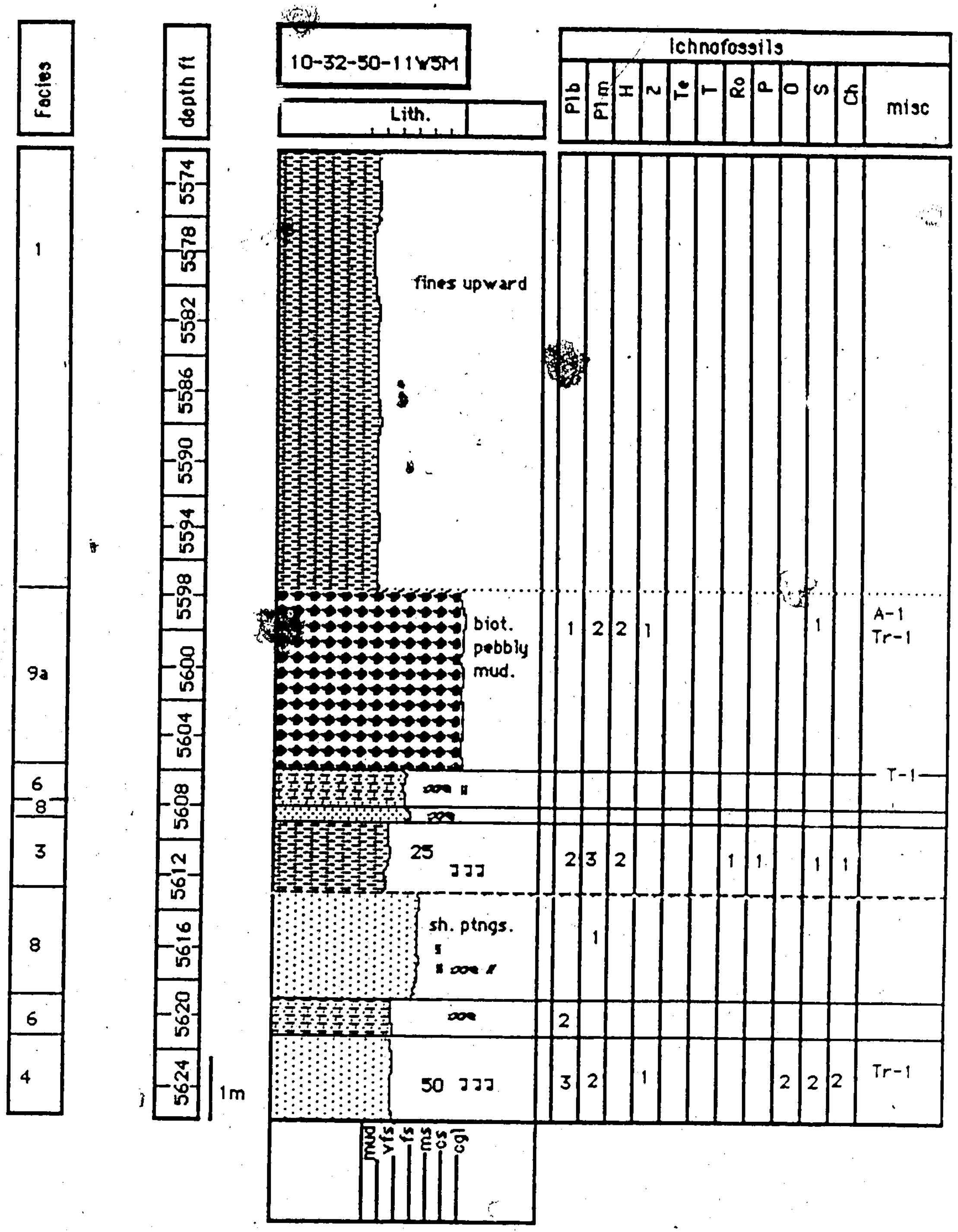
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Tr-1
T-1
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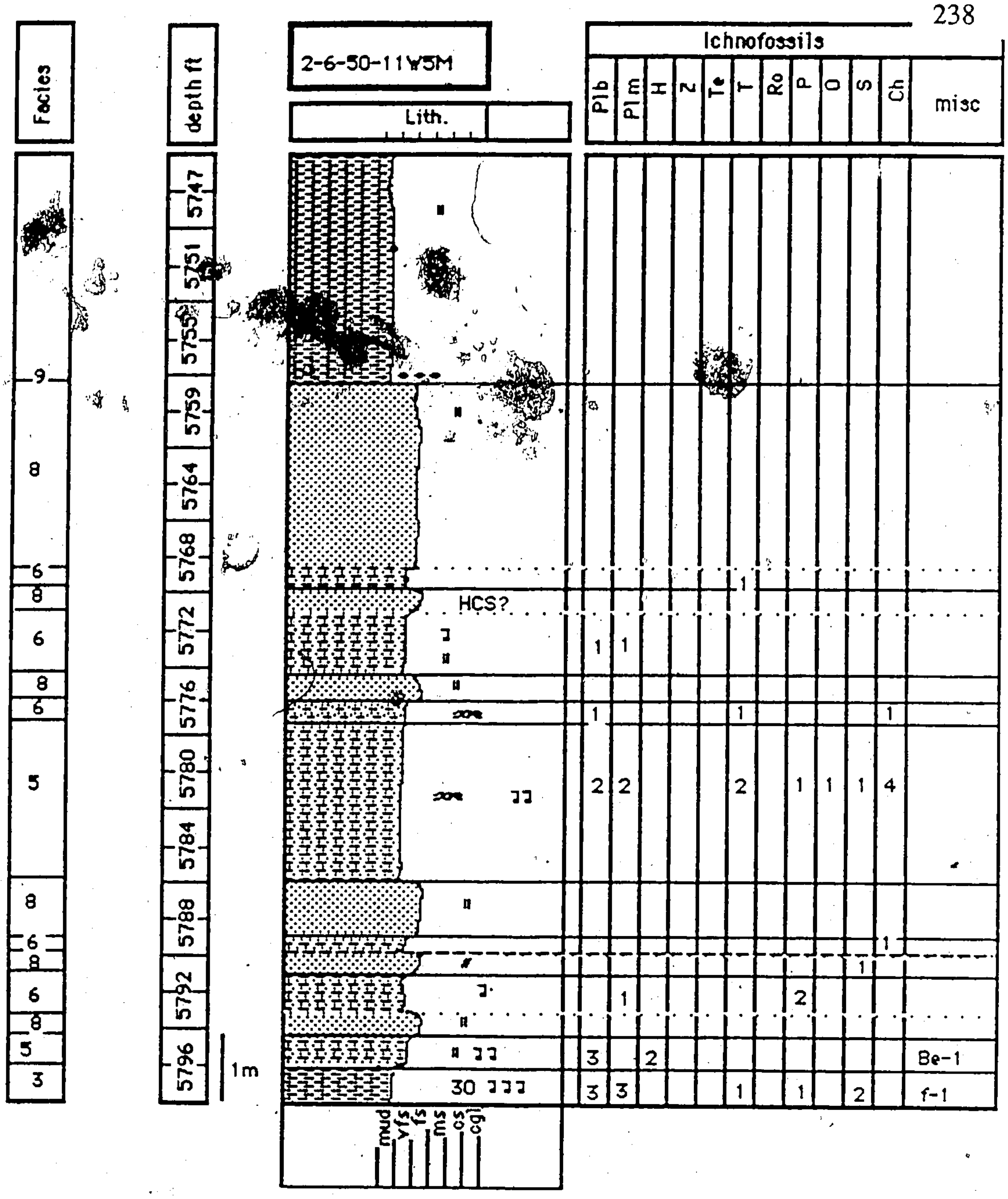
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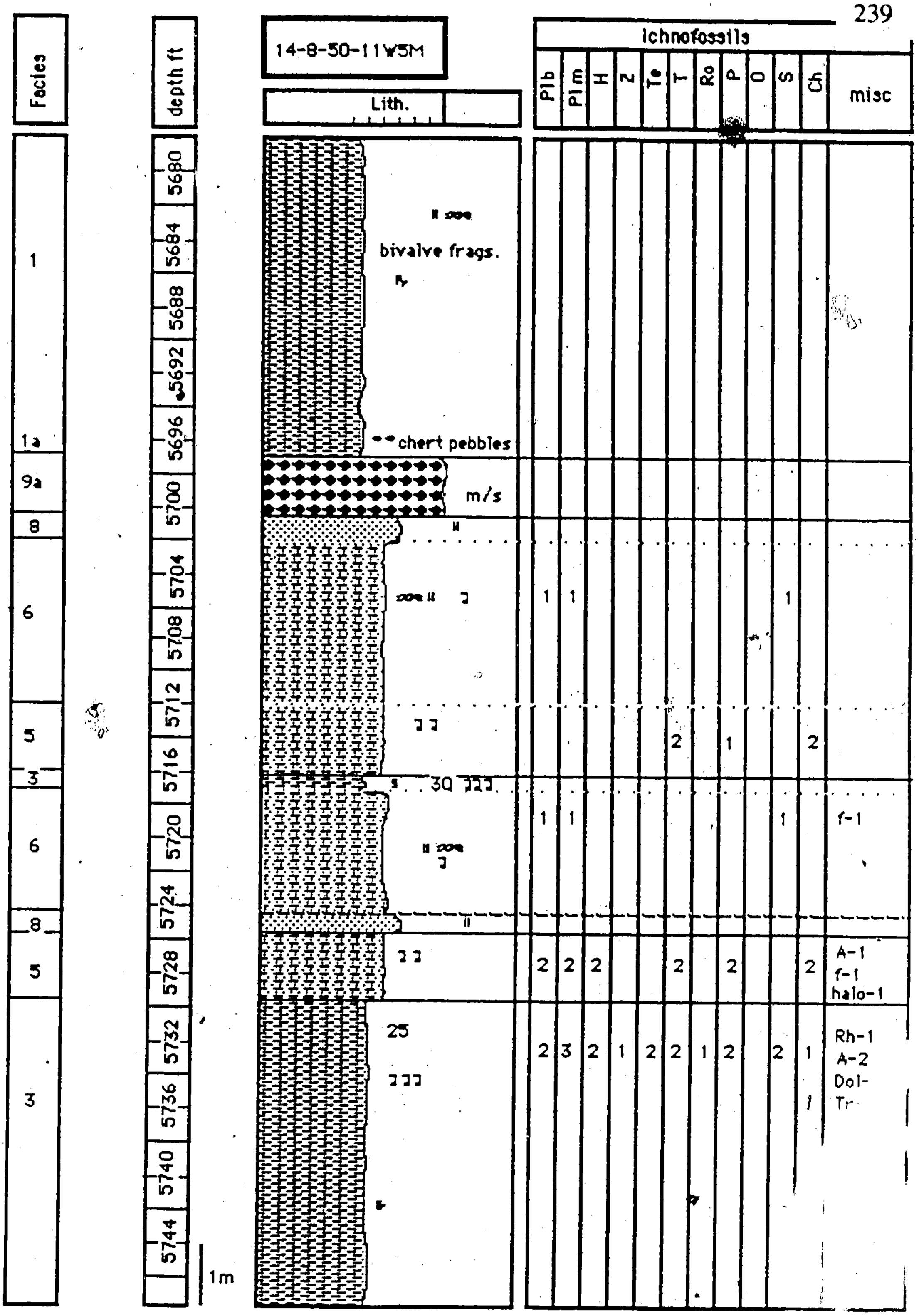
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chert pebbles
m/s
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2 1 2
1 1 1
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Dol-
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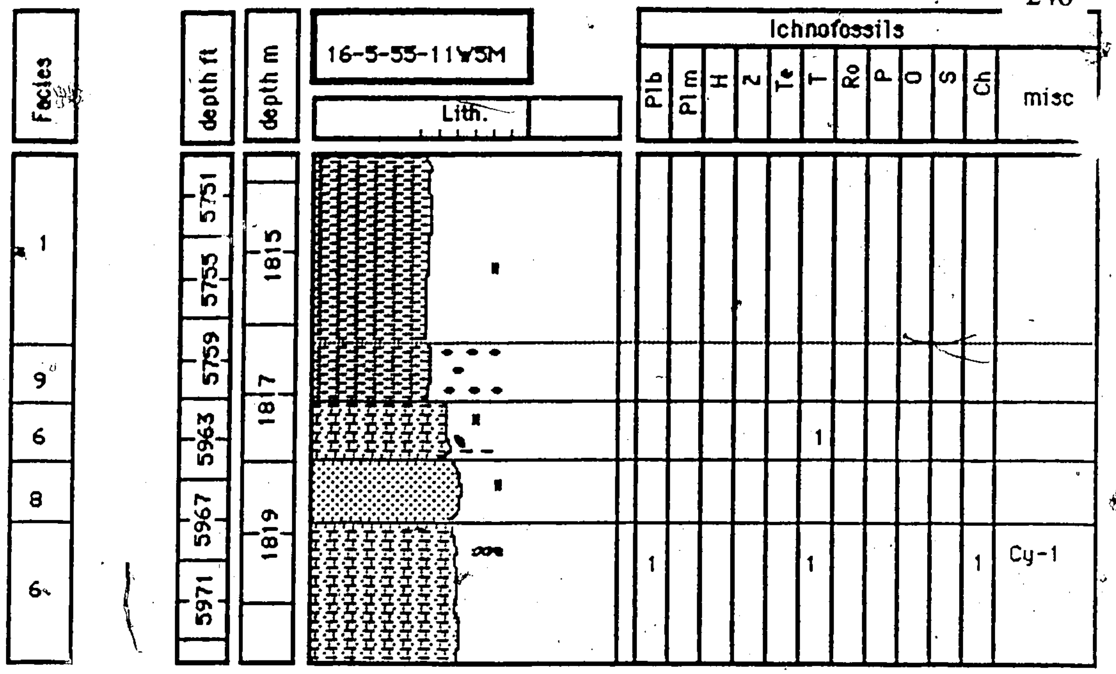
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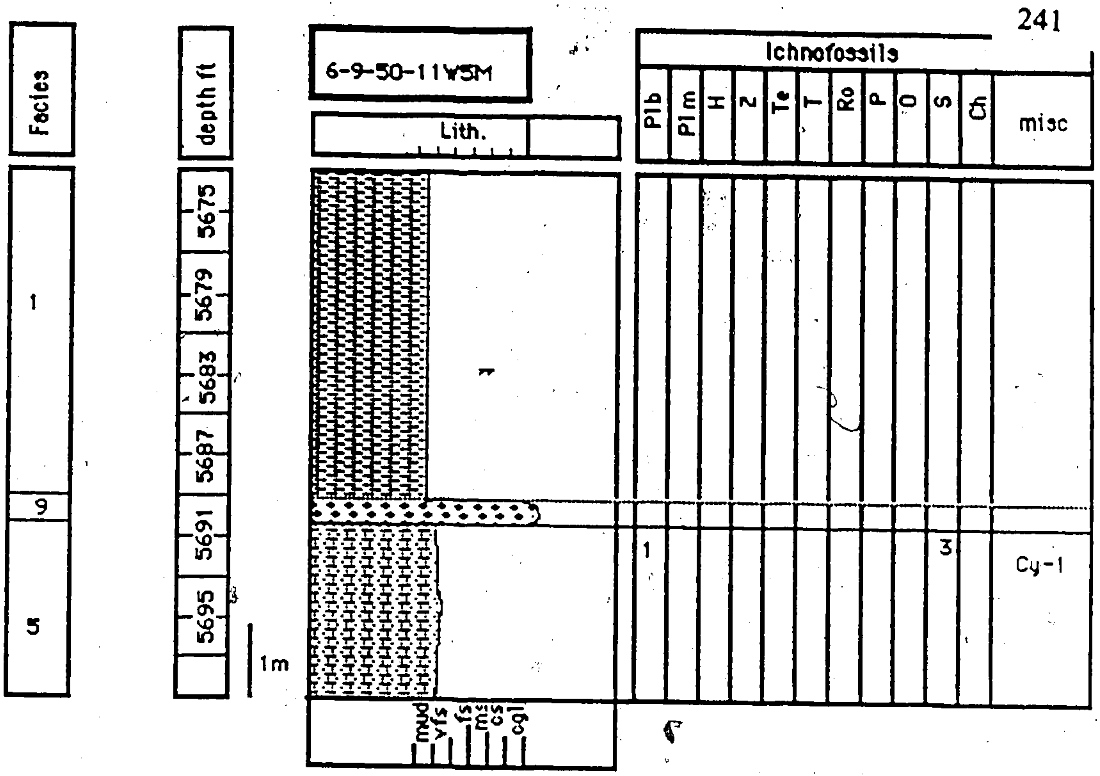
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mud
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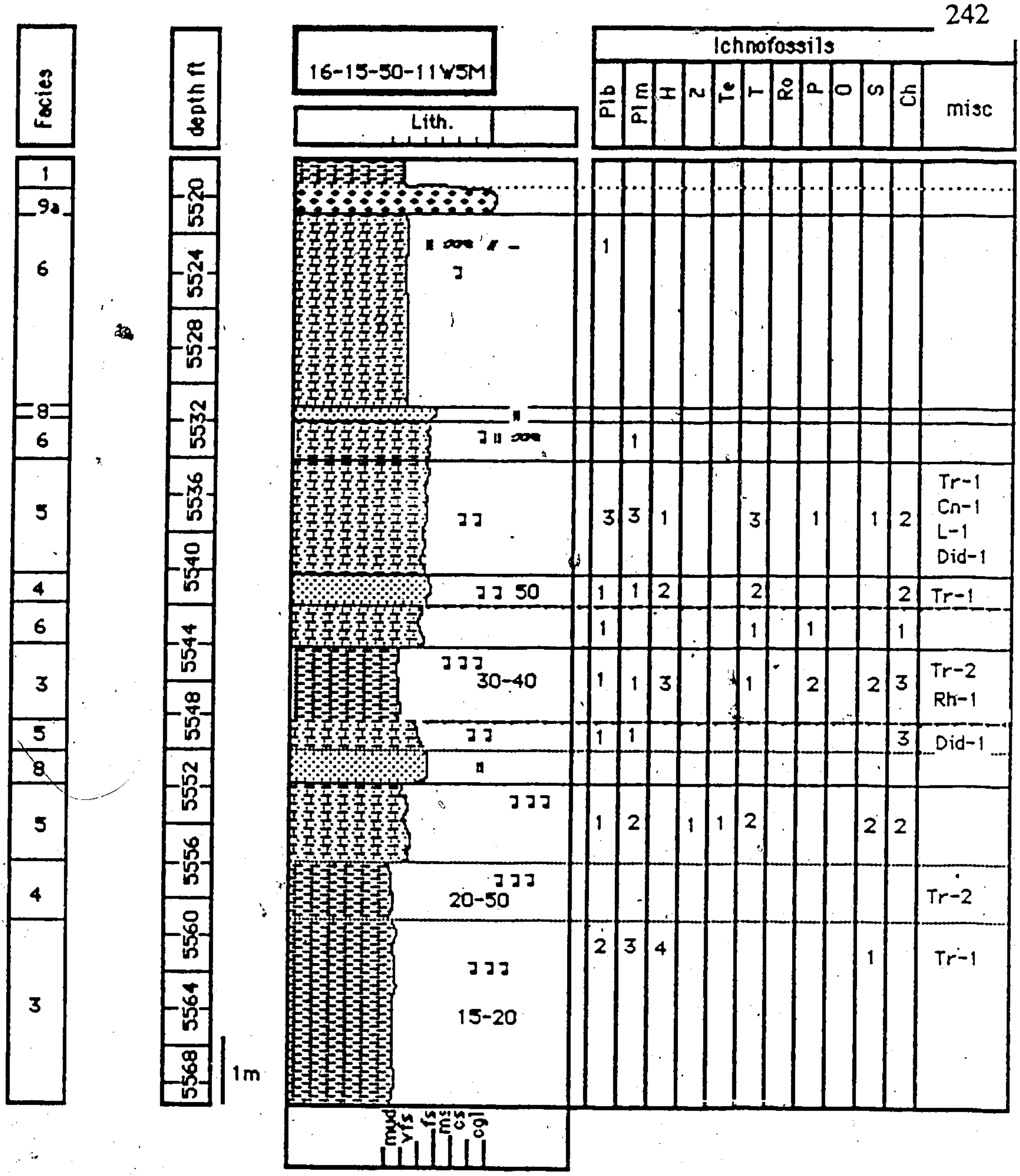
Cy-1



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9a													
6		1											
8													
6			1										
5		3	3	1			3		1		1	2	Tr-1 Cn-1 L-1 Did-1
4	50	1	1	2			2					2	Tr-1
6		1					1		1			1	
3	30-40	1	1	3			1		2		2	3	Tr-2 Rh-1
5		1	1									3	Did-1
8													
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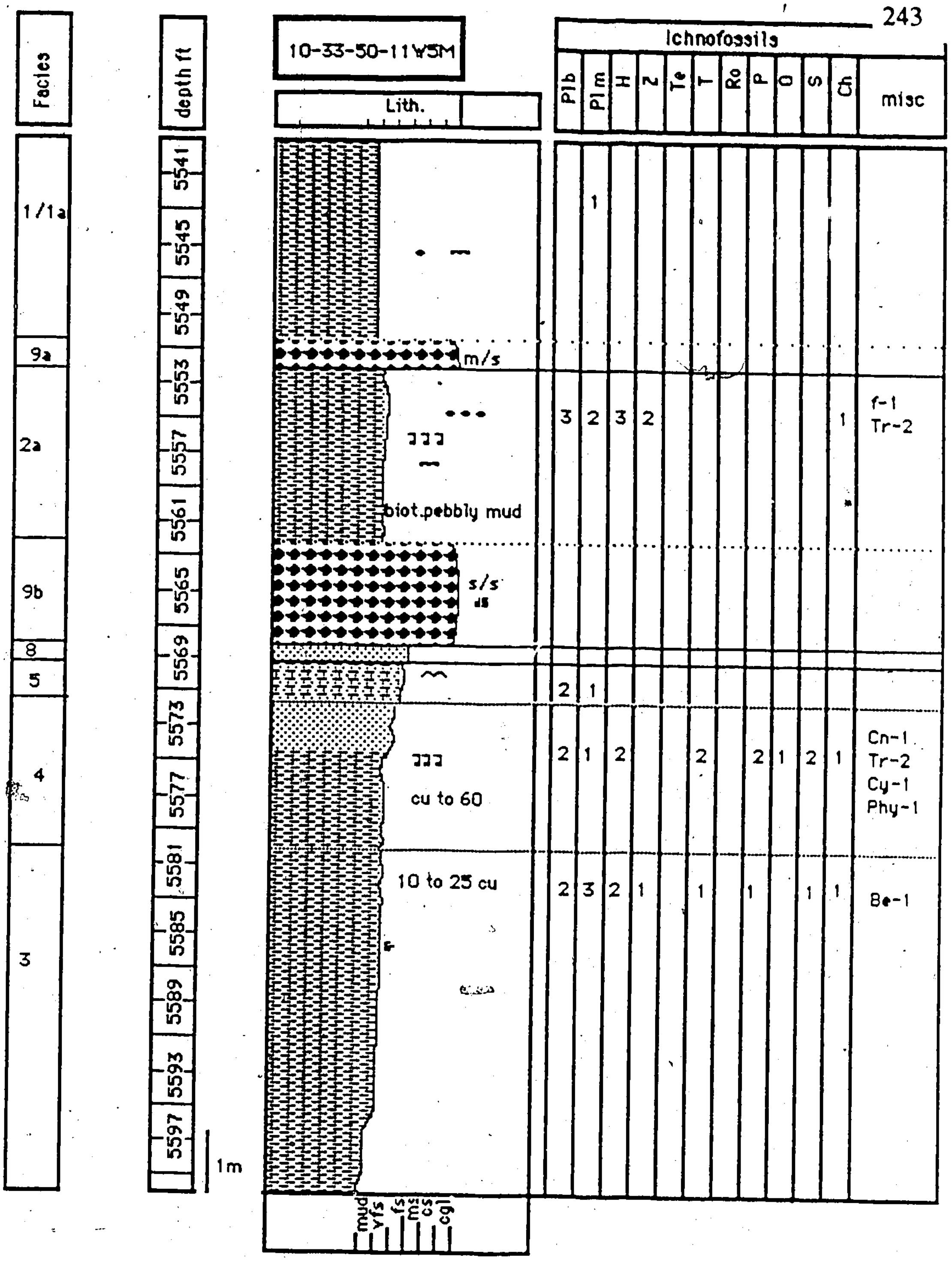
3	15-20	2	3	4							1		Tr-1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Plm
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S
Ch
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9a
2a
9b
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1m
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3 2 3 2 1
f-1
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2 1
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Cy-1
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Be-1
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fs
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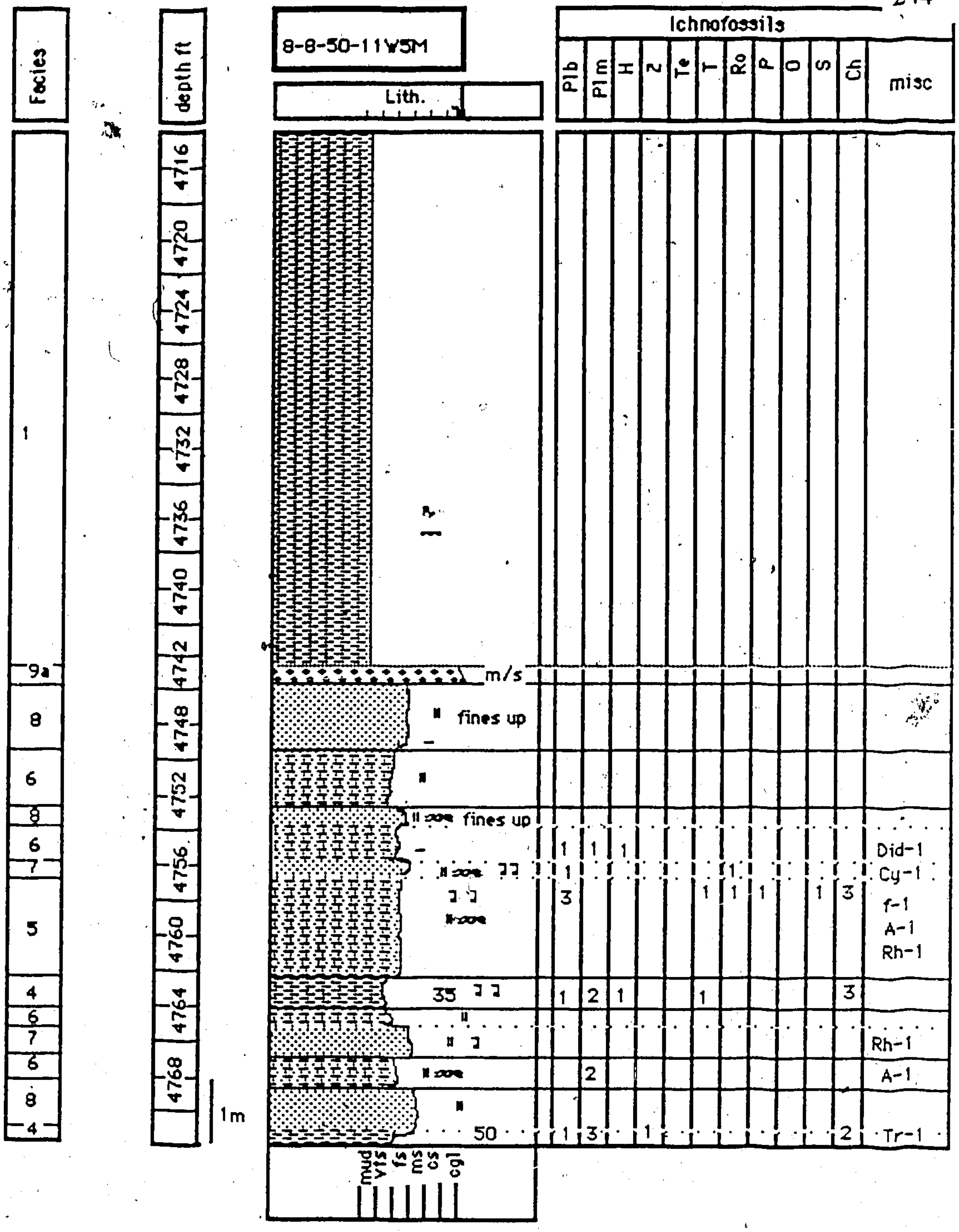
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misc
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m/s
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1 2 1 1 3
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1 3 1 2
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Cy-1
f-1
A-1
Rh-1
Rh-1
A-1
Tr-1
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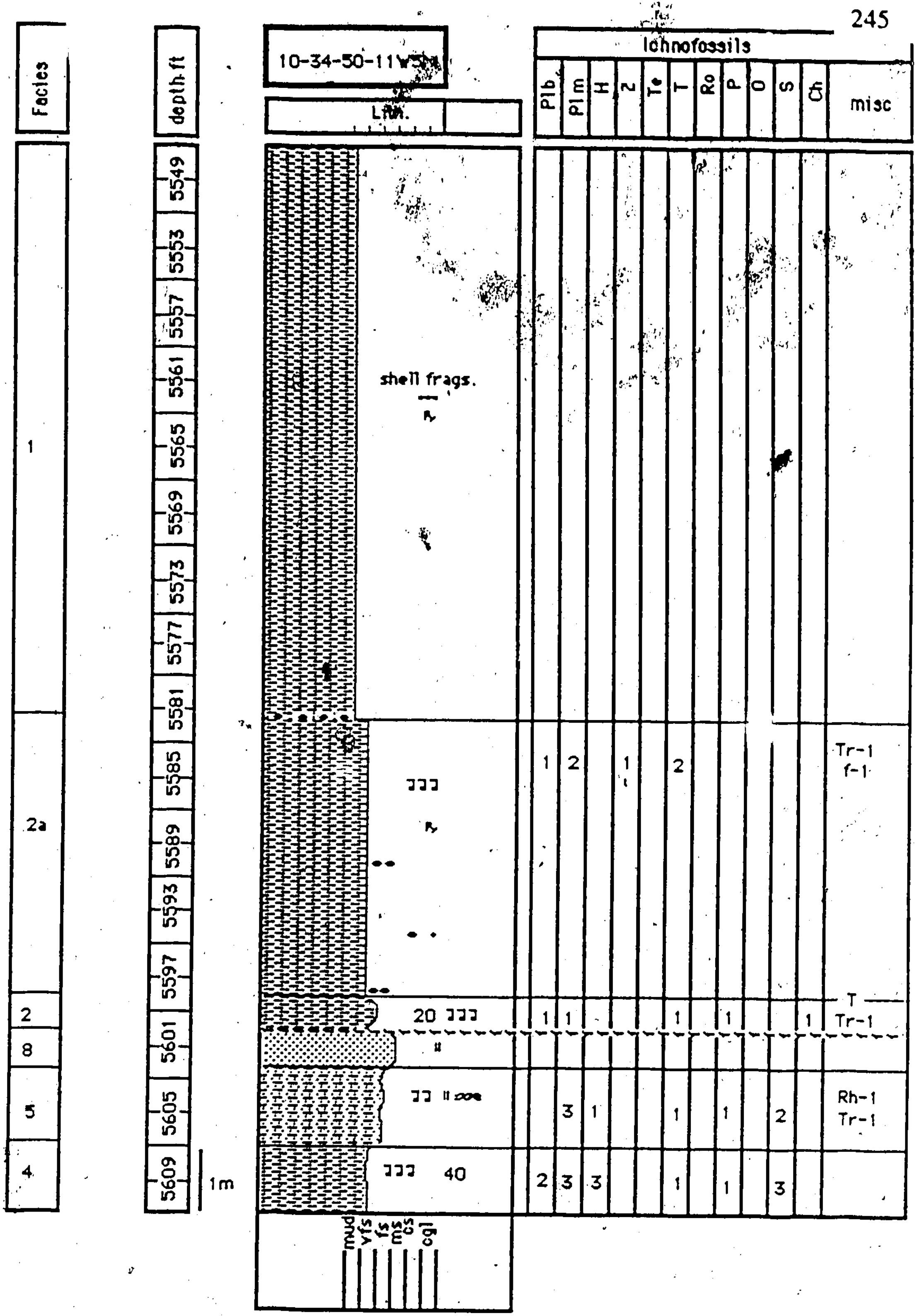
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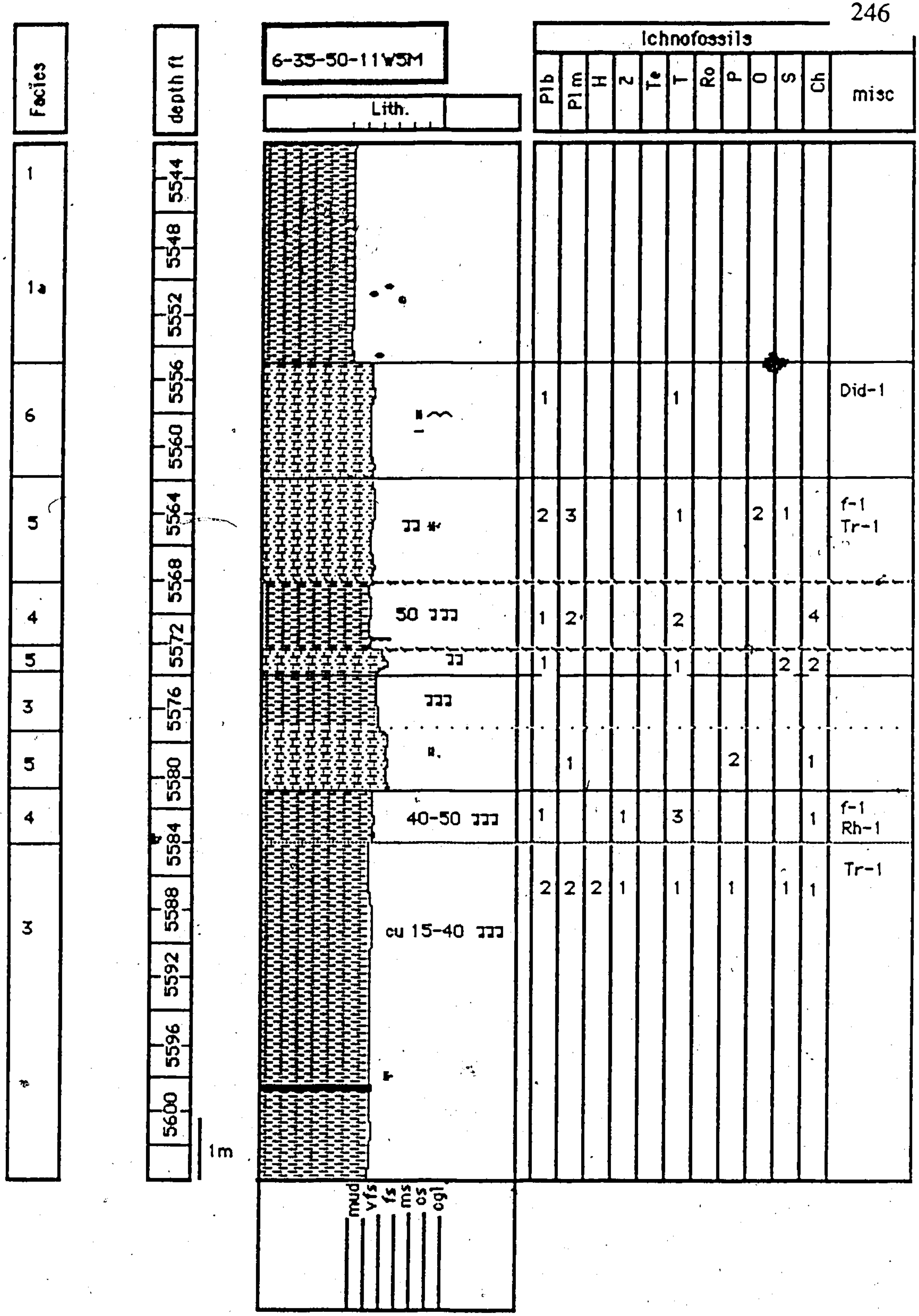
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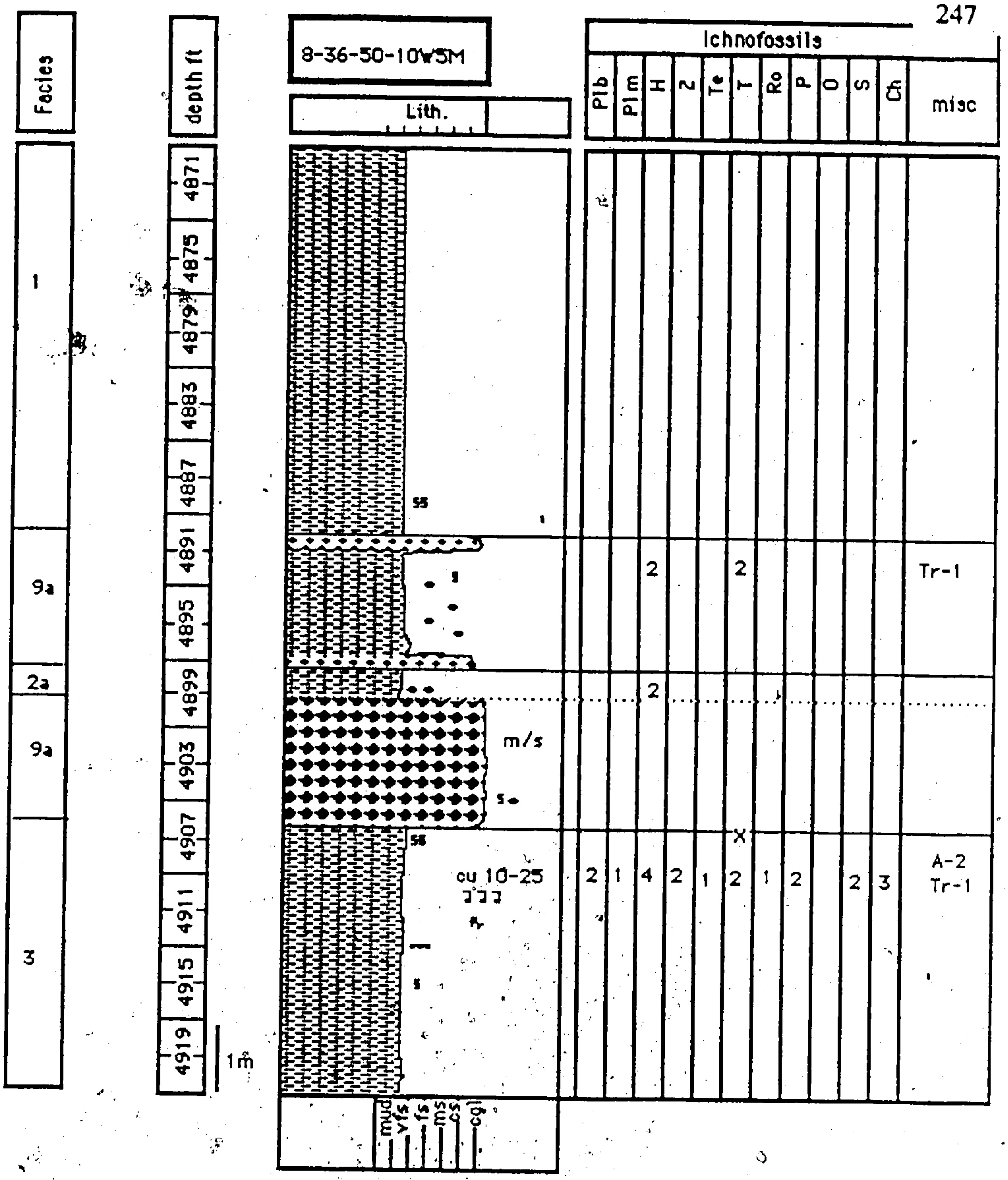
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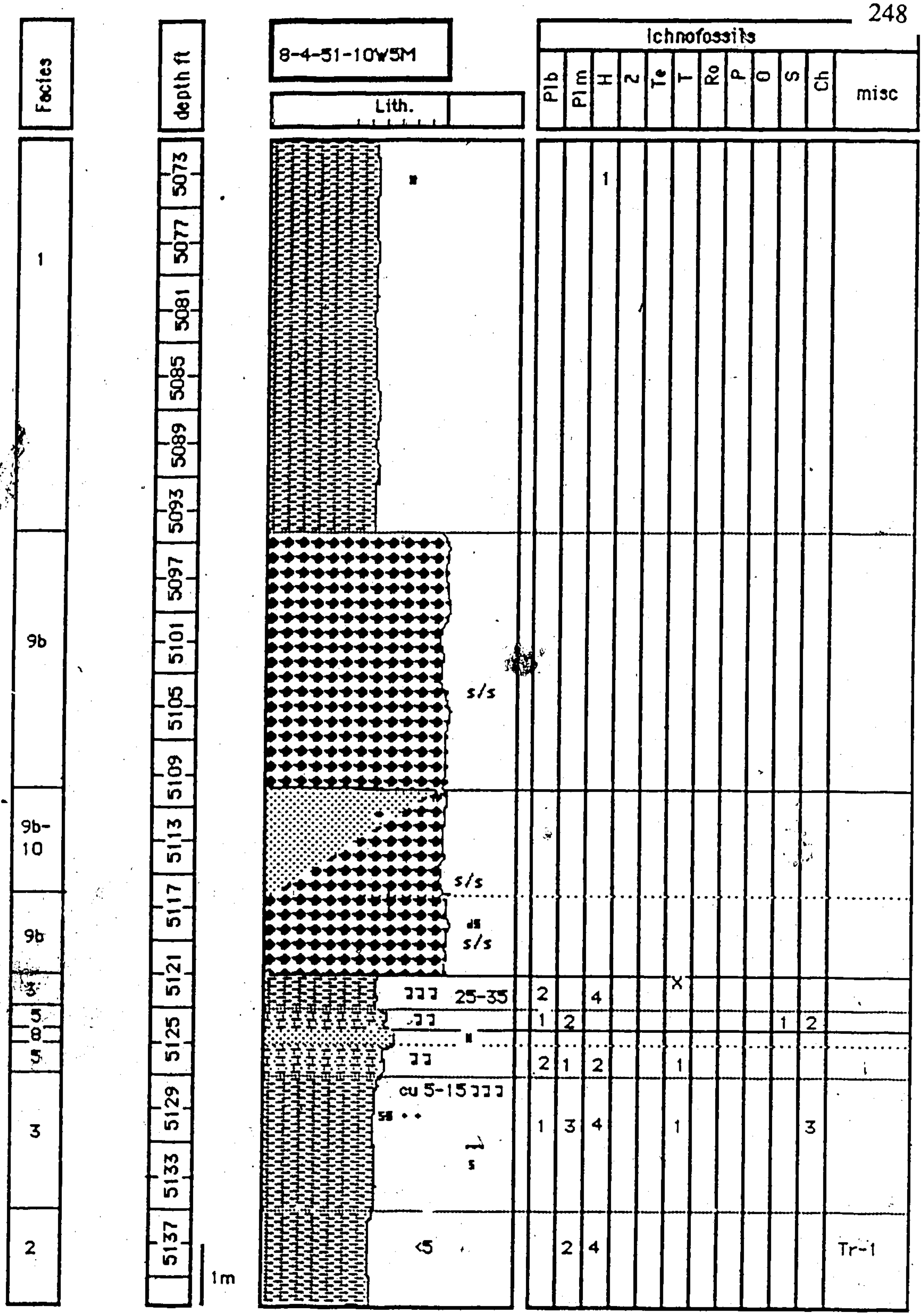
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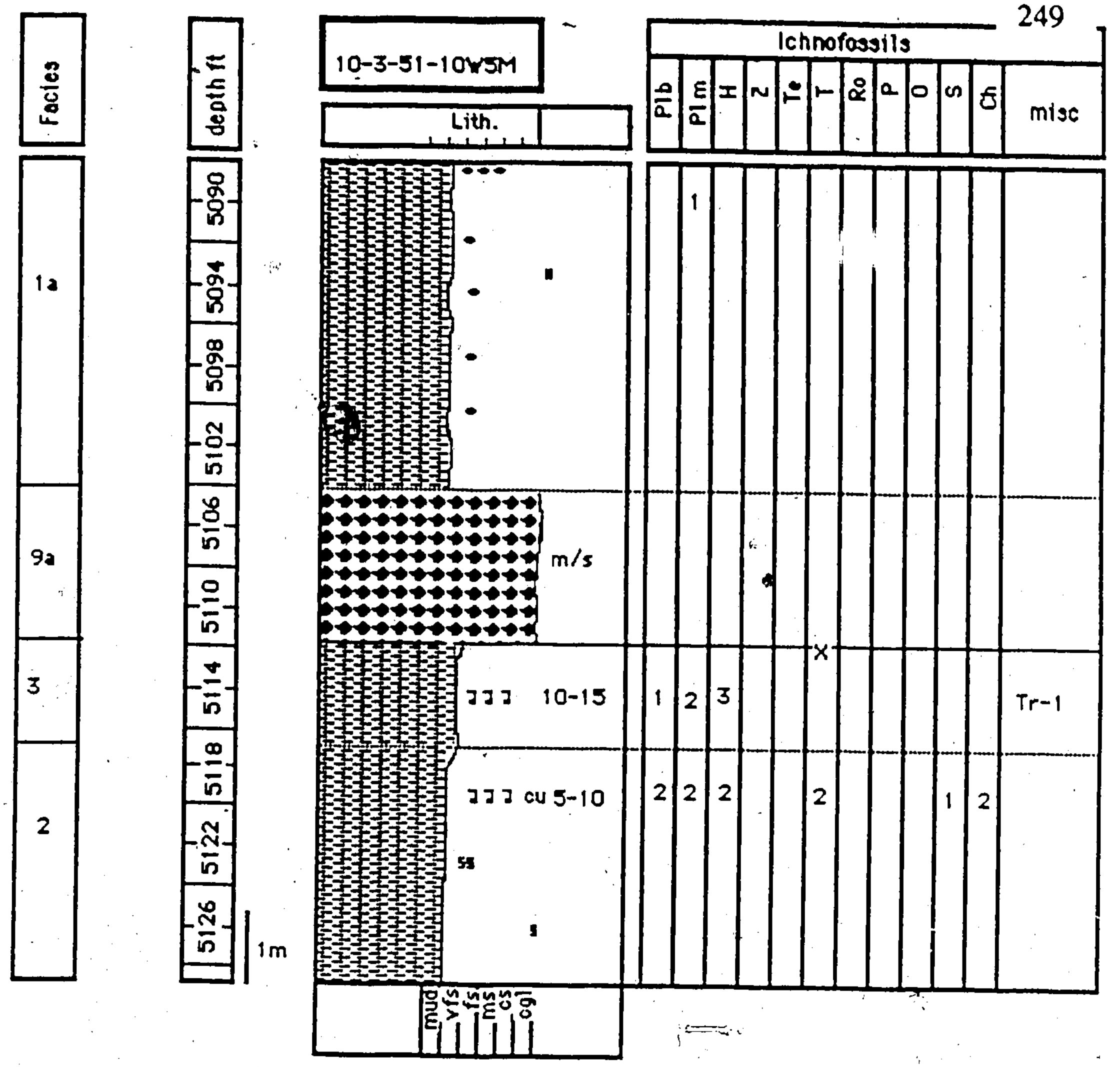
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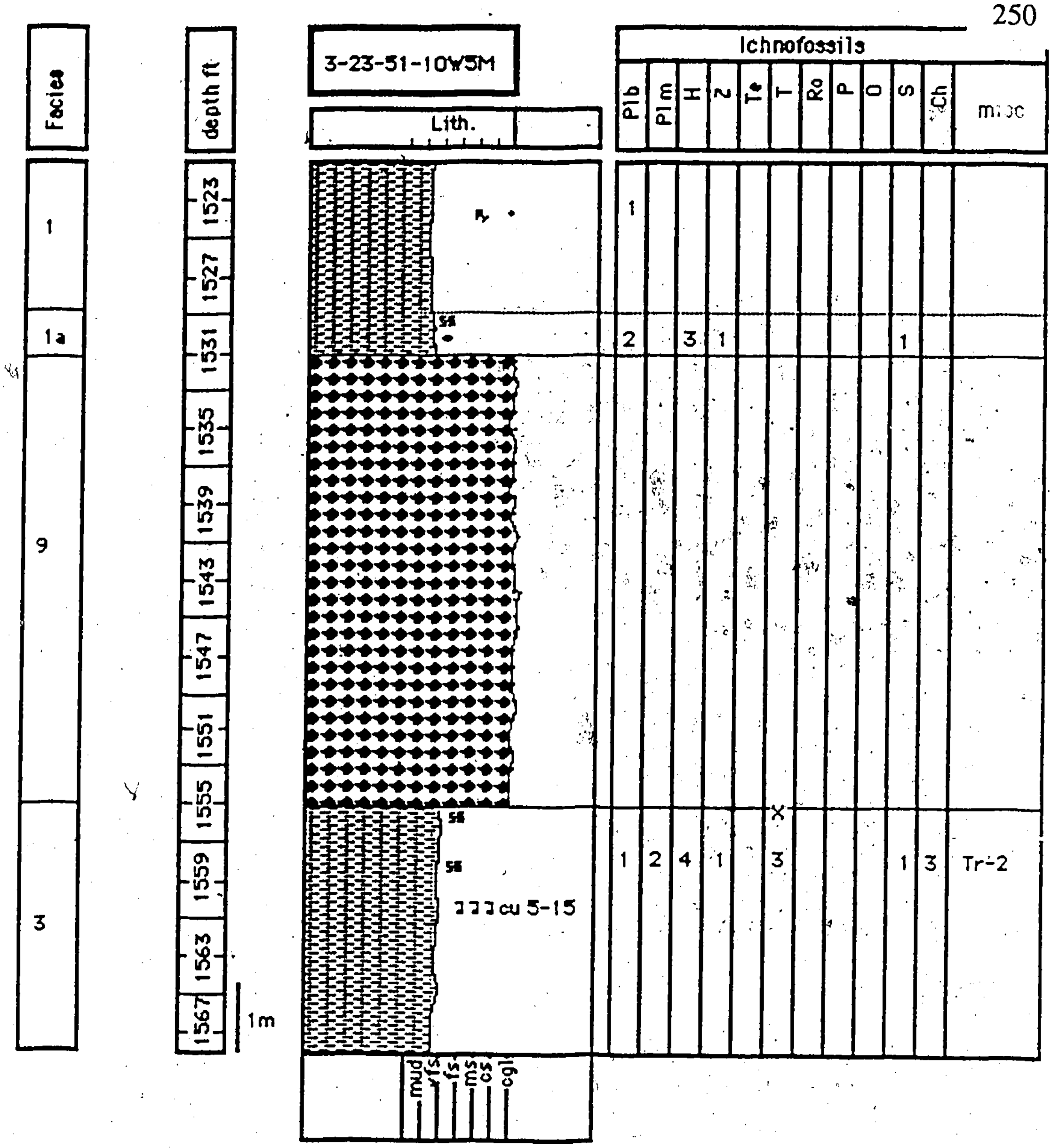
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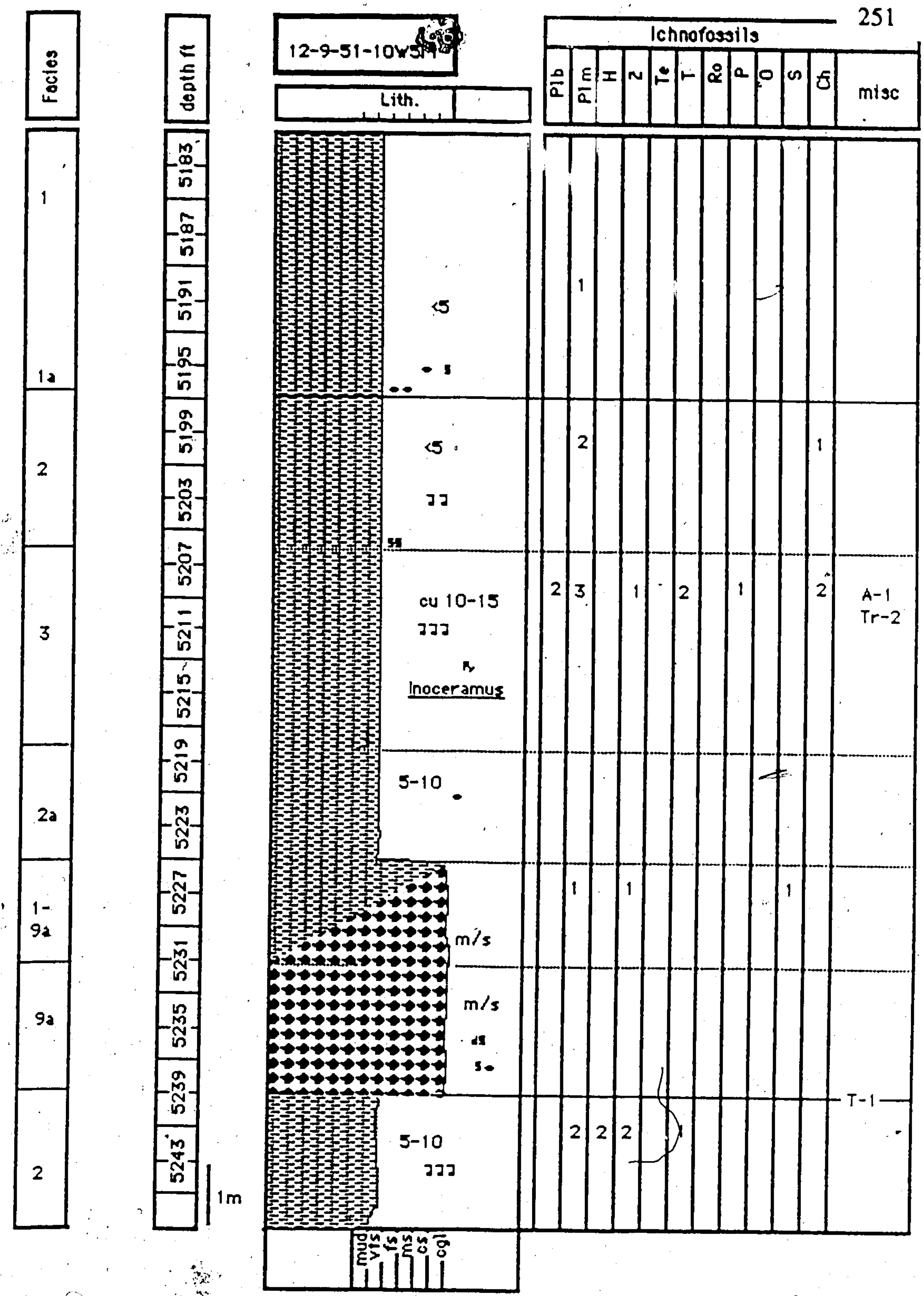
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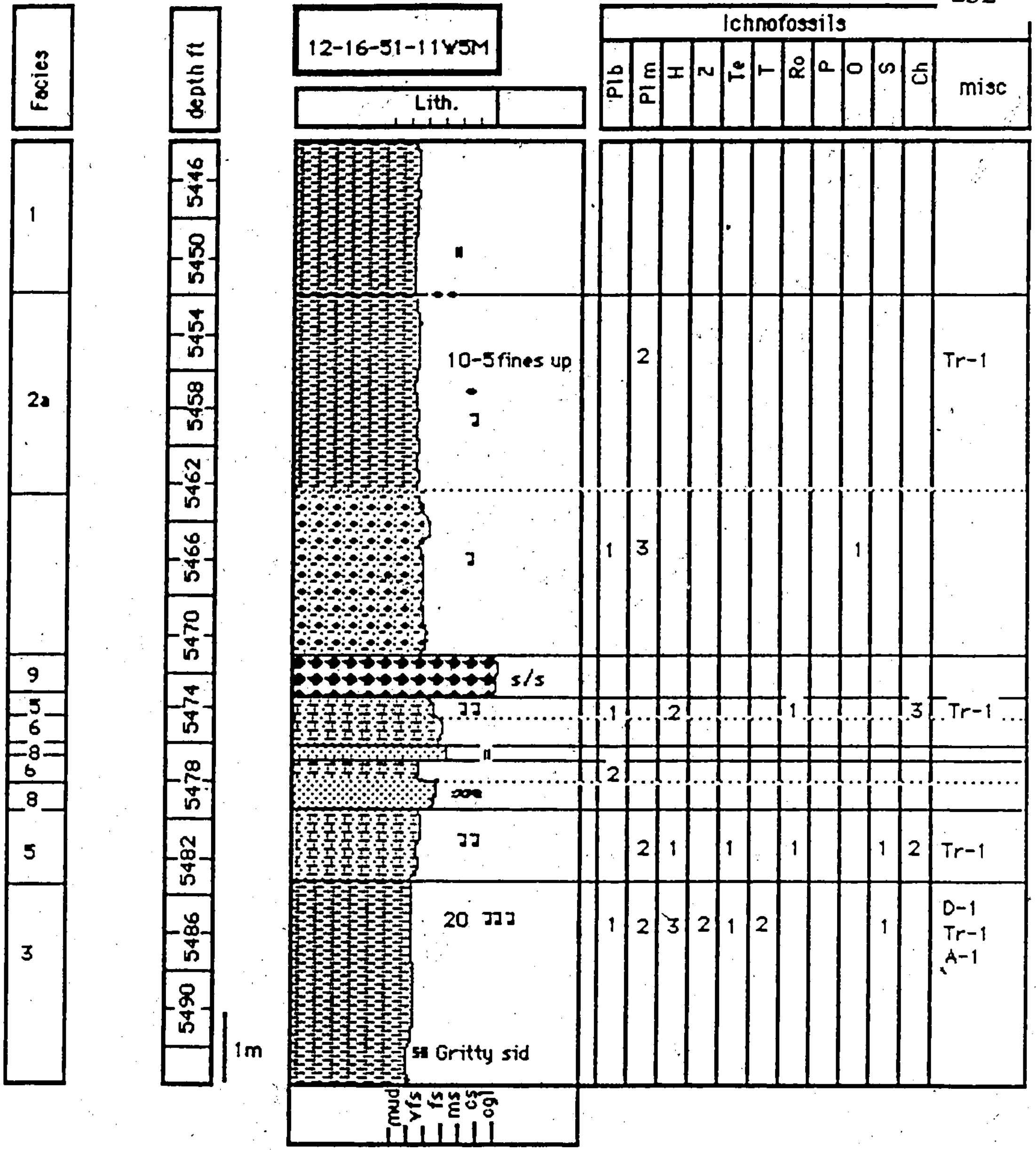
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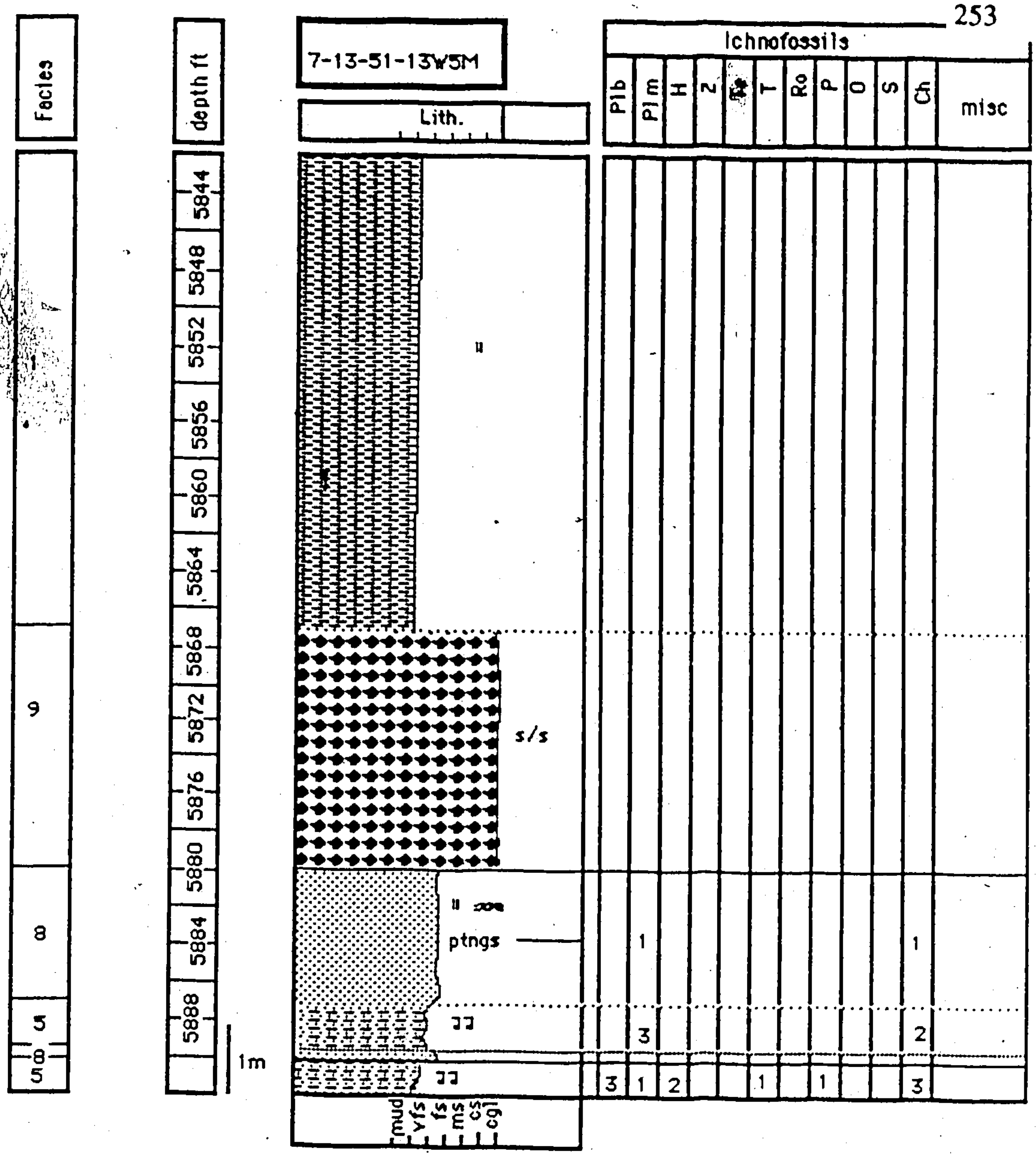
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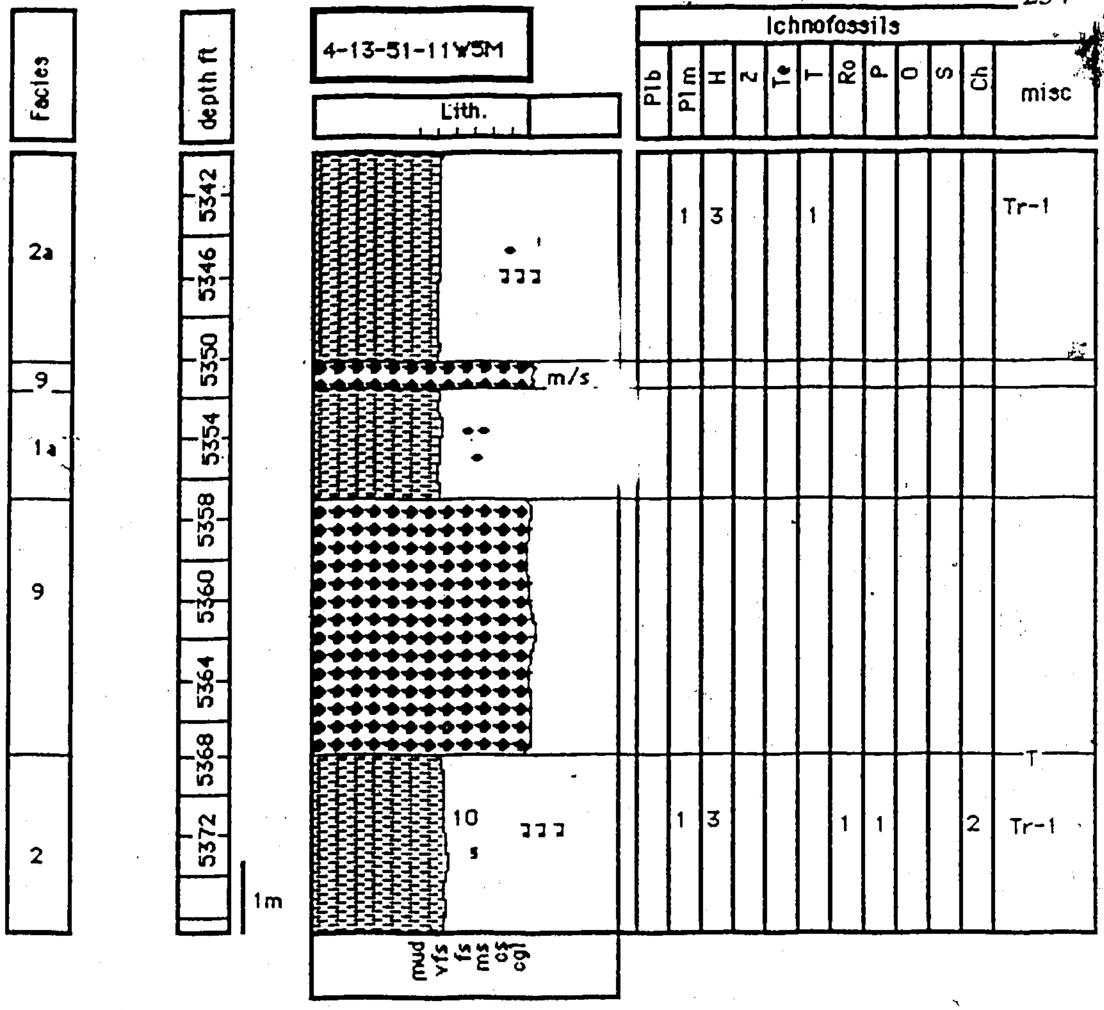
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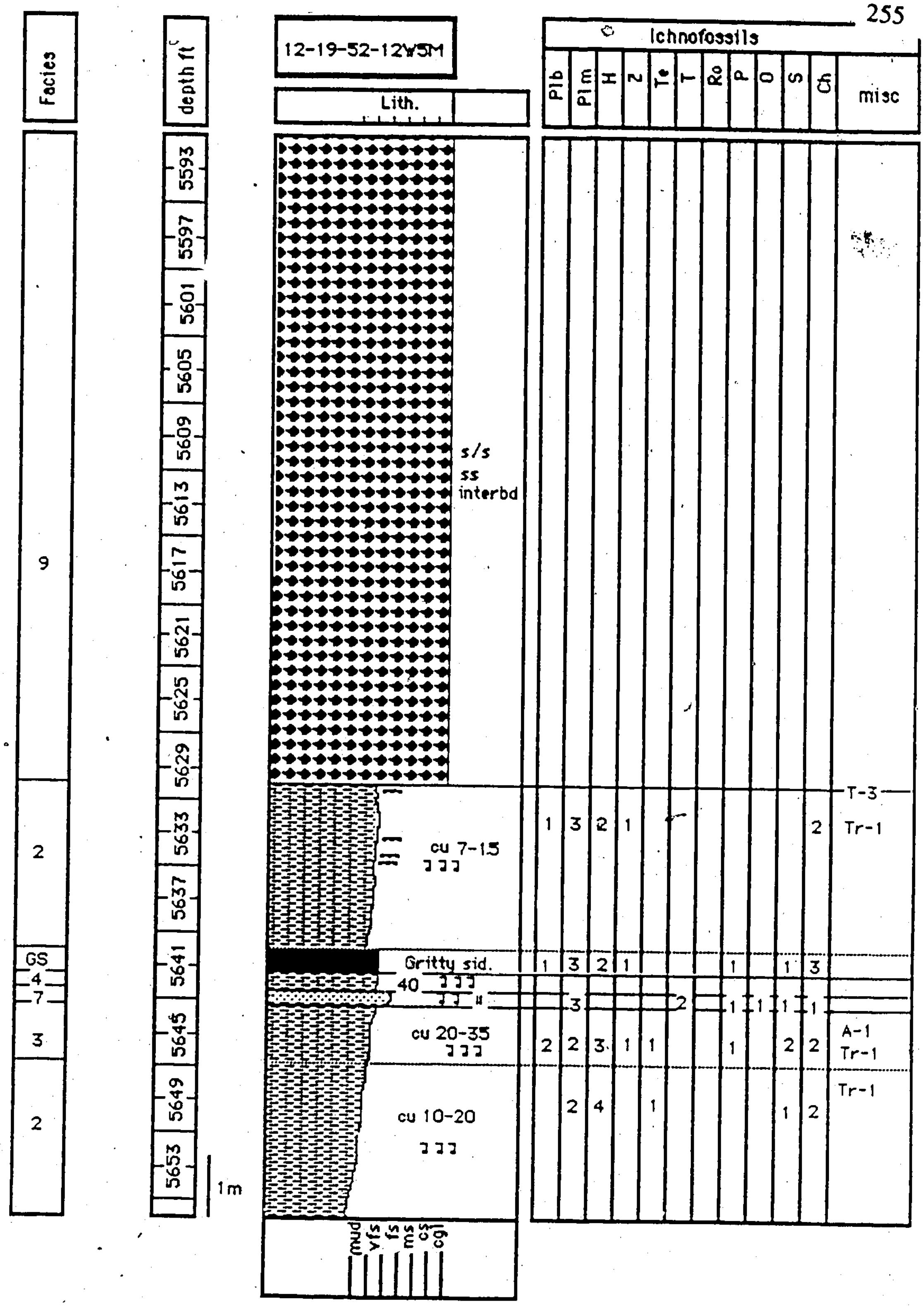
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A-1
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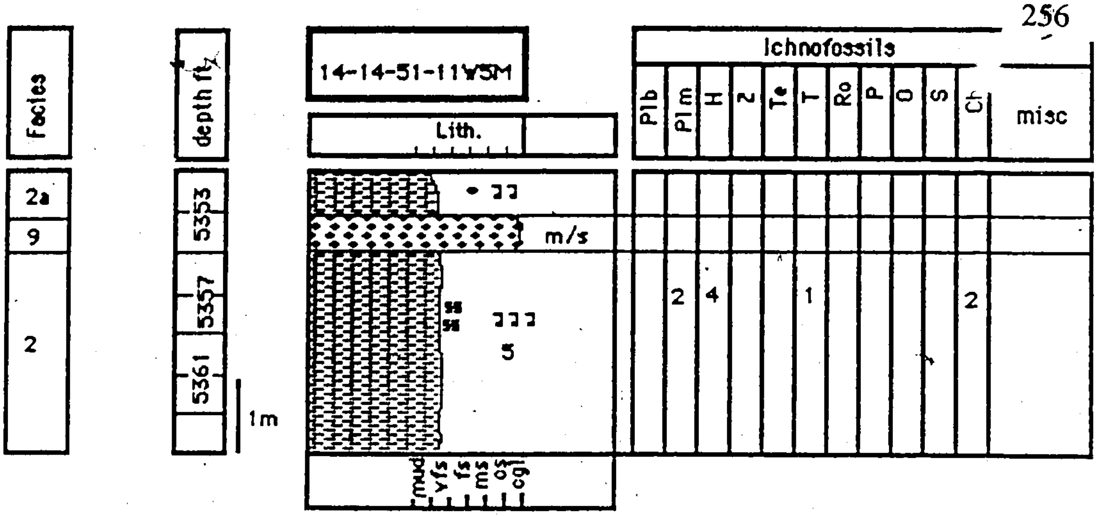
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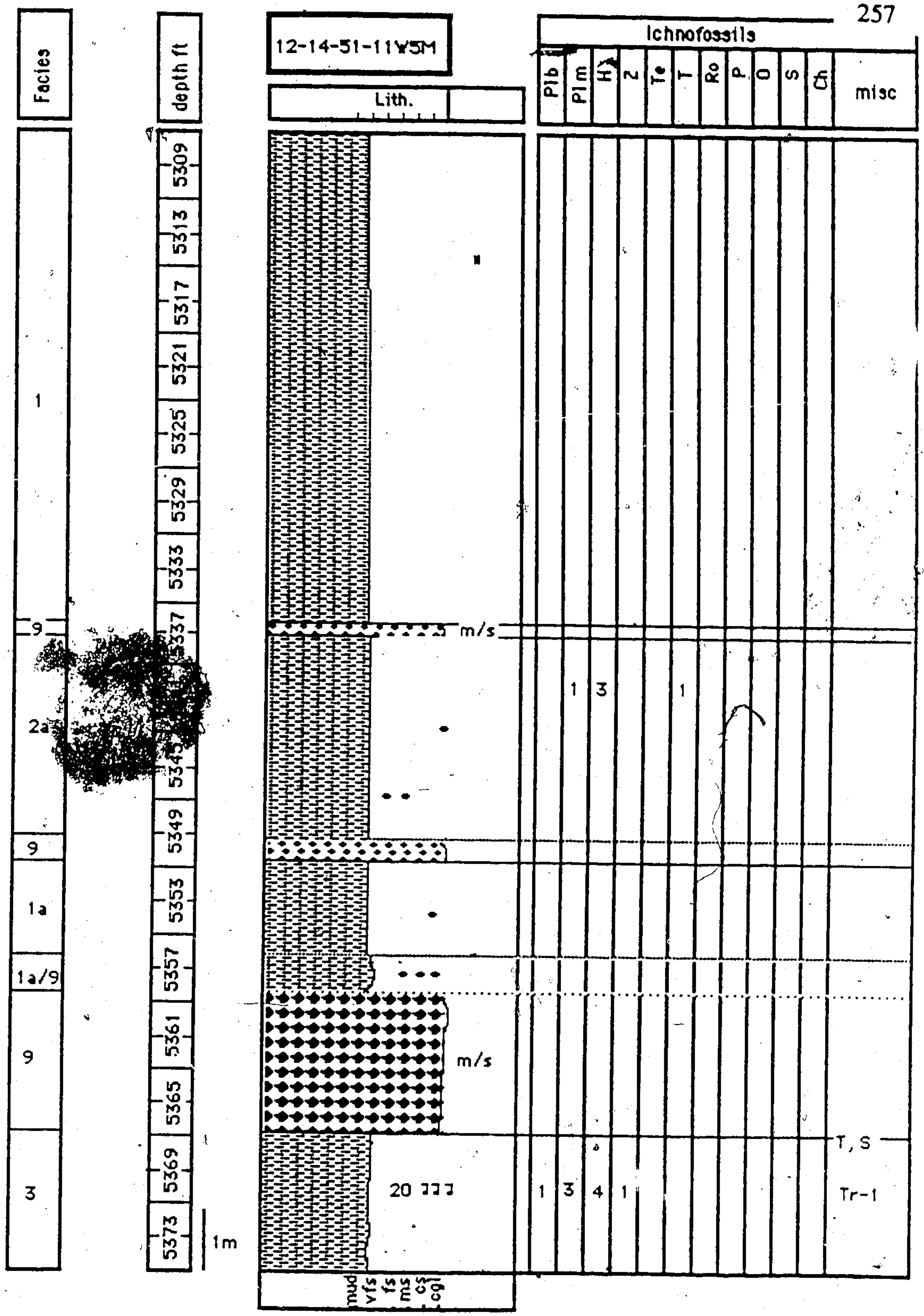
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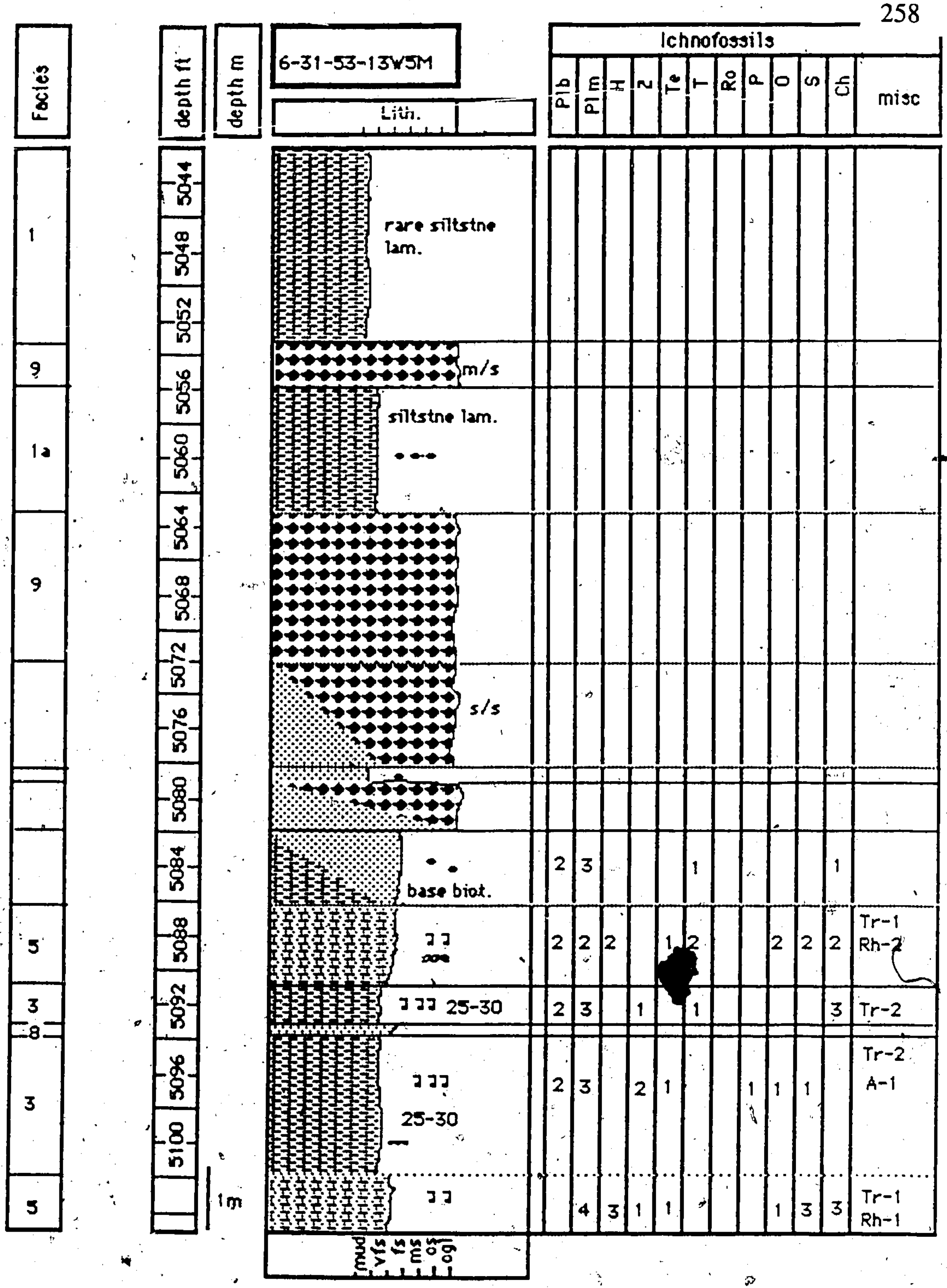
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Rh-2
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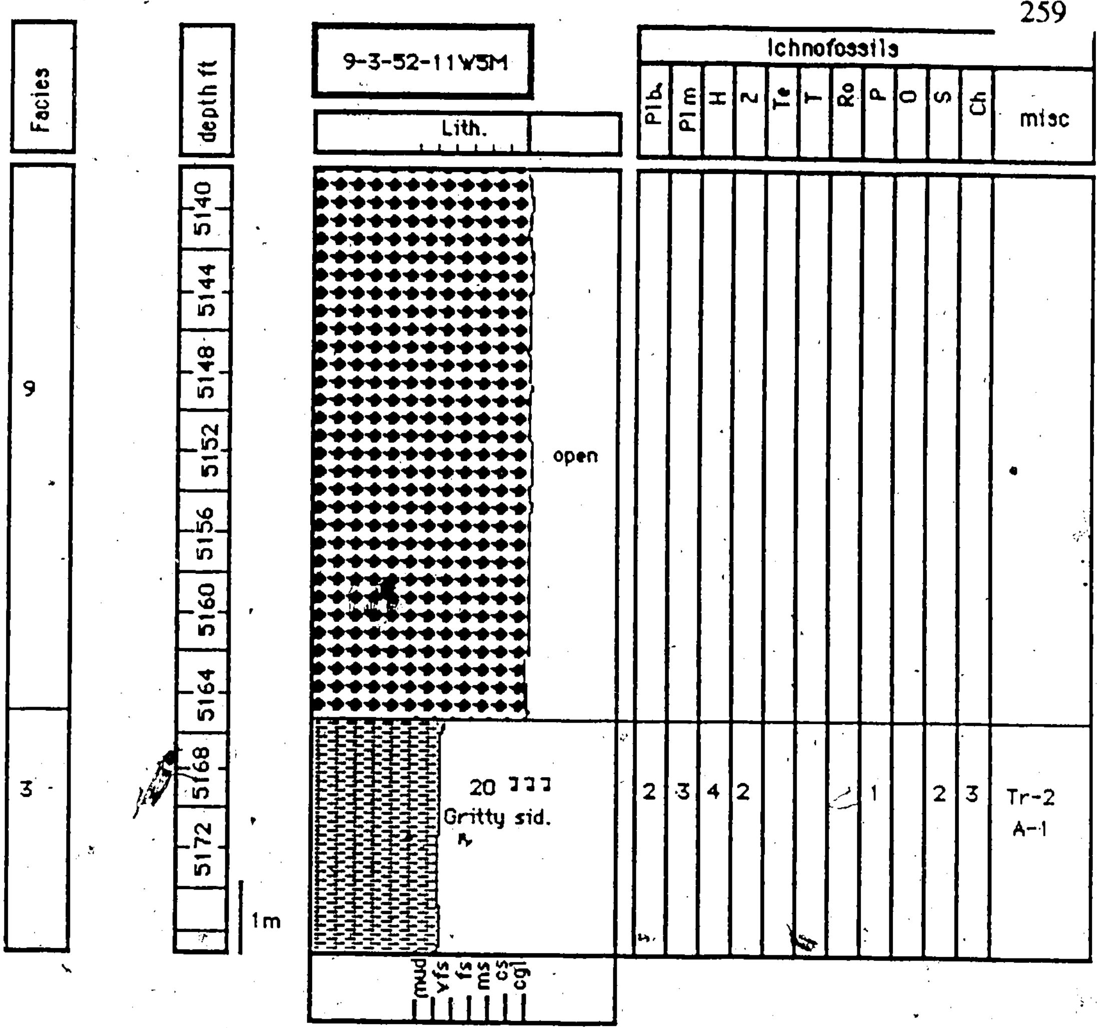
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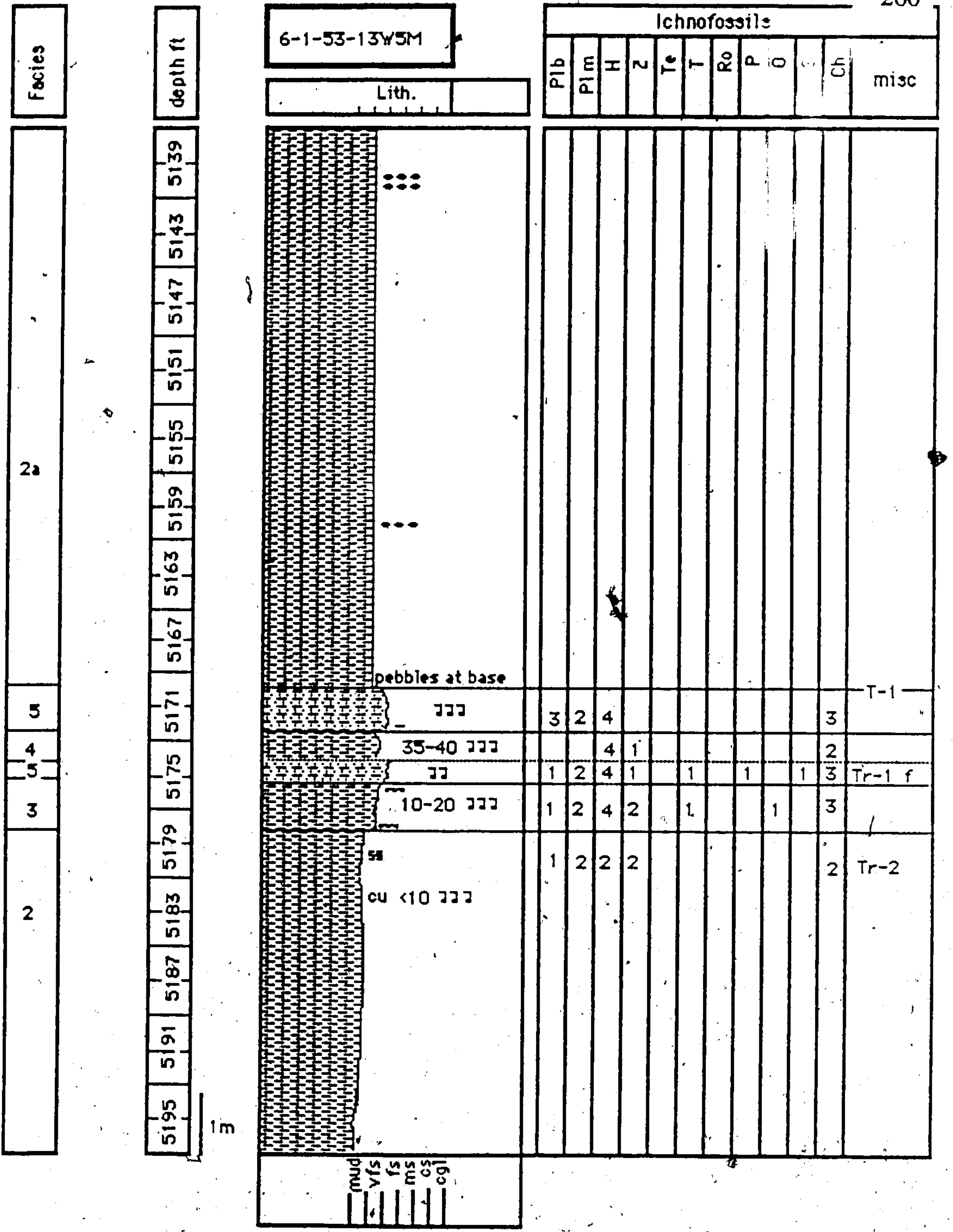
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6-1-53-13W5M
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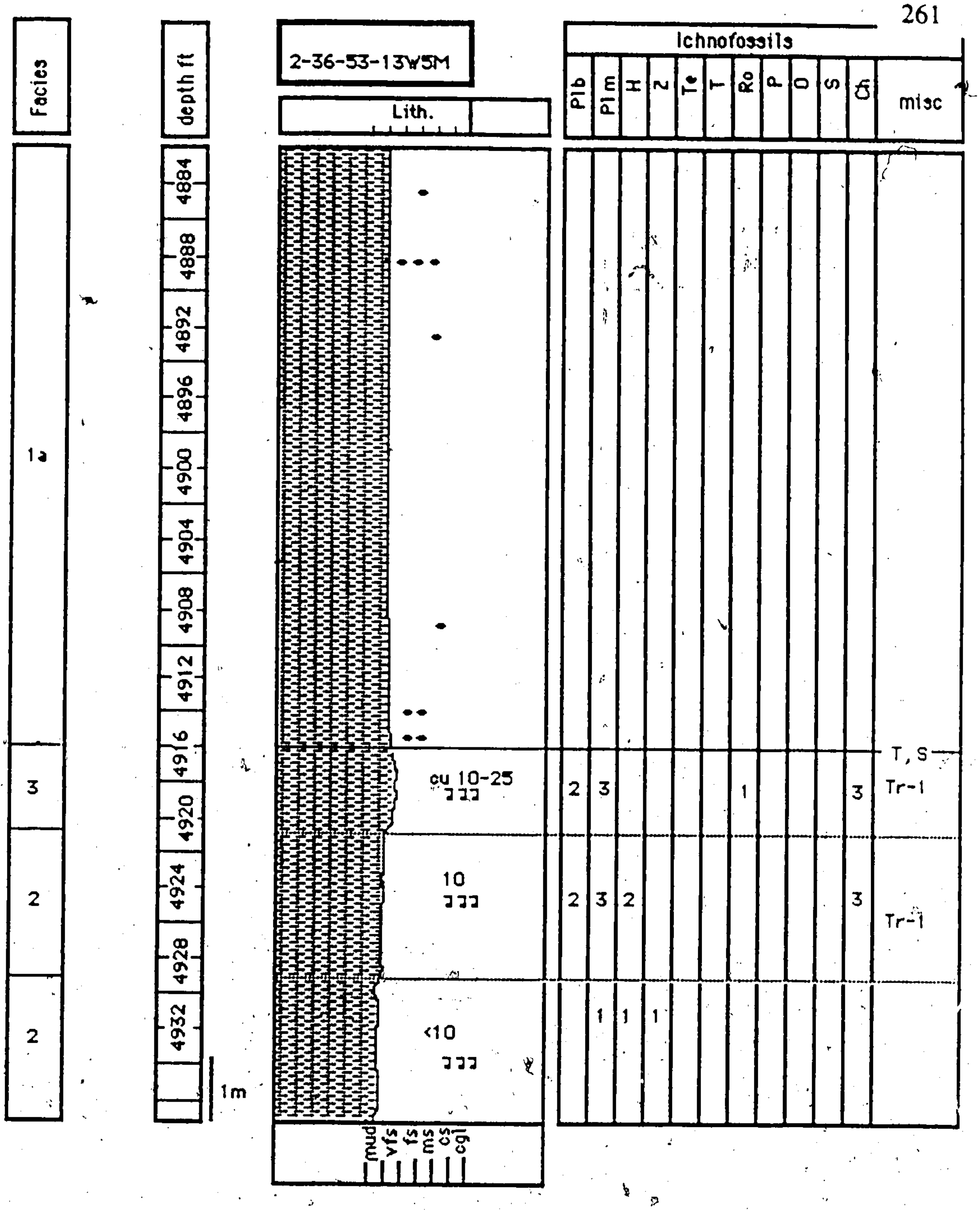
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cs
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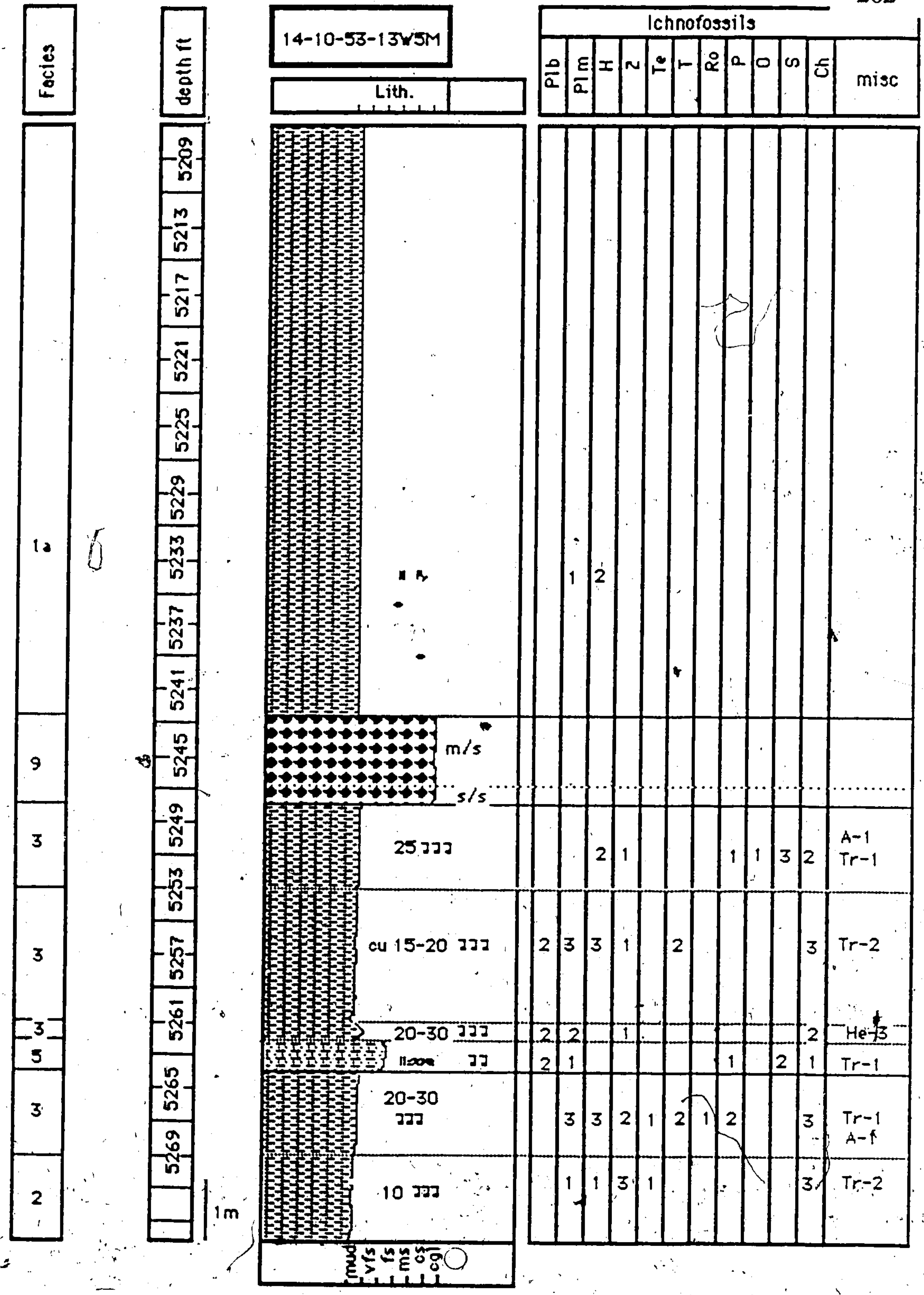
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misc
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A-f
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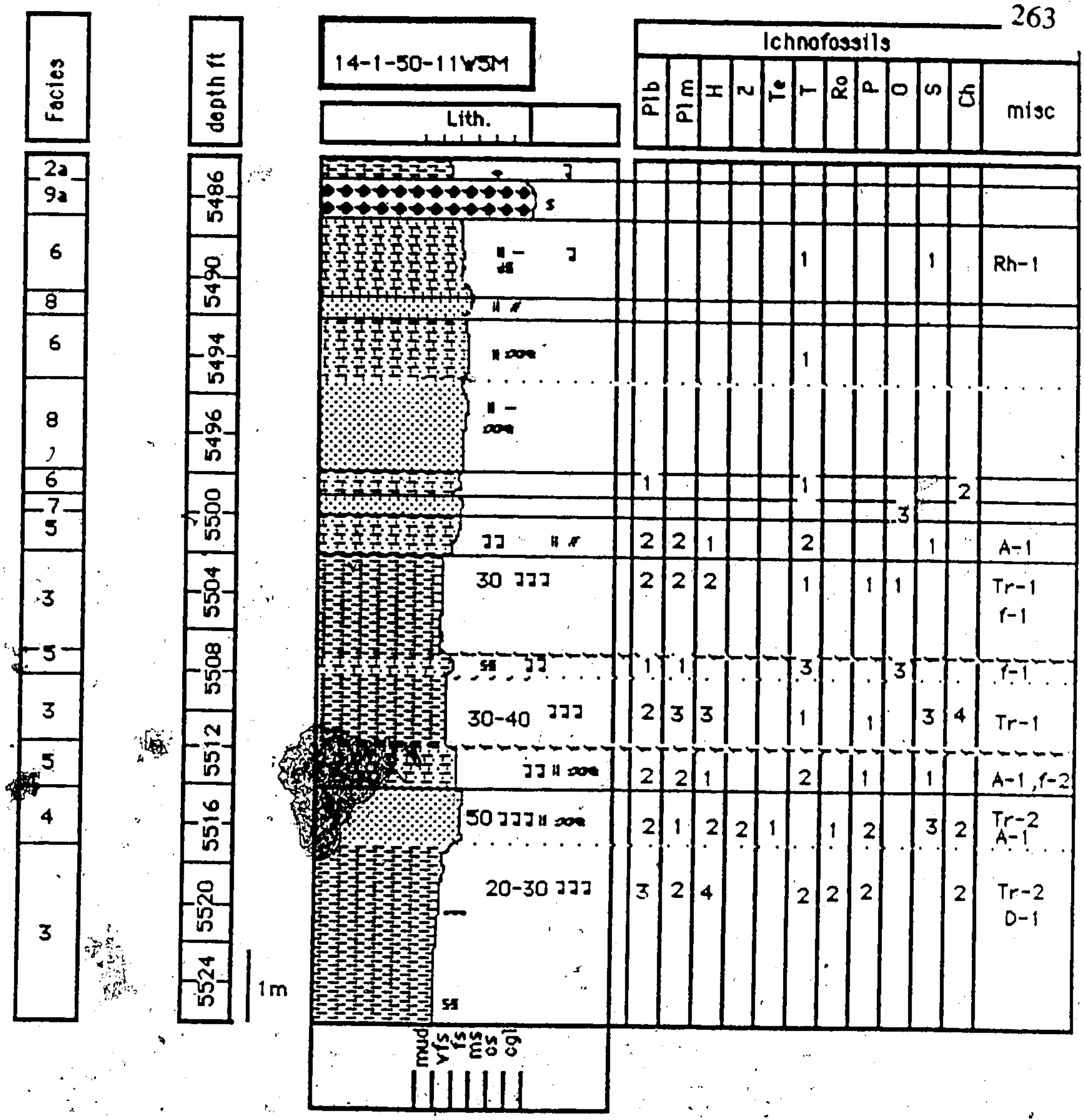

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5520
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1m
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30-40
50
20-30
Rh-1
A-1
Tr-1
f-1
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Tr-2
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Tr-2
D-1
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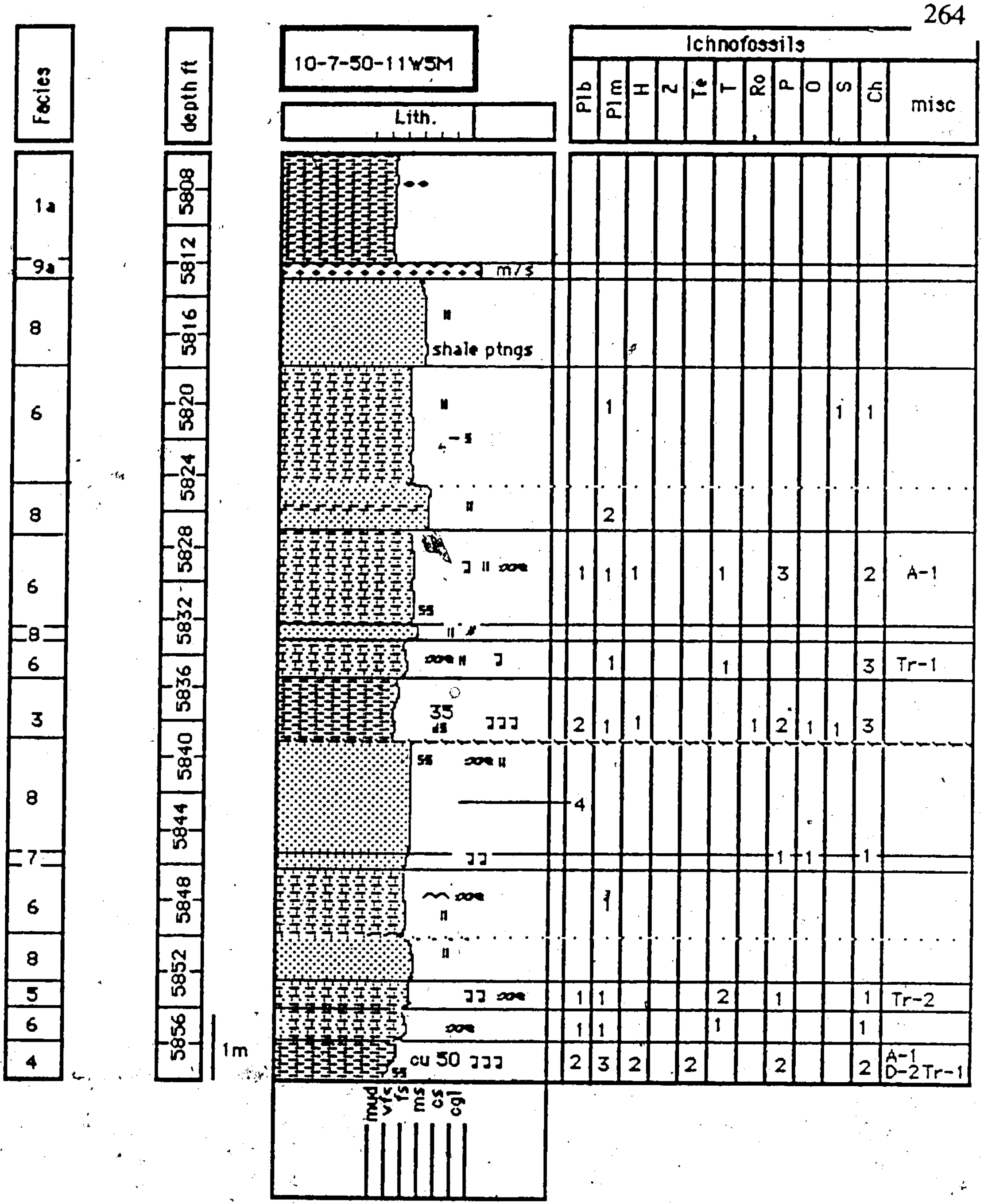
ms
cs
cgl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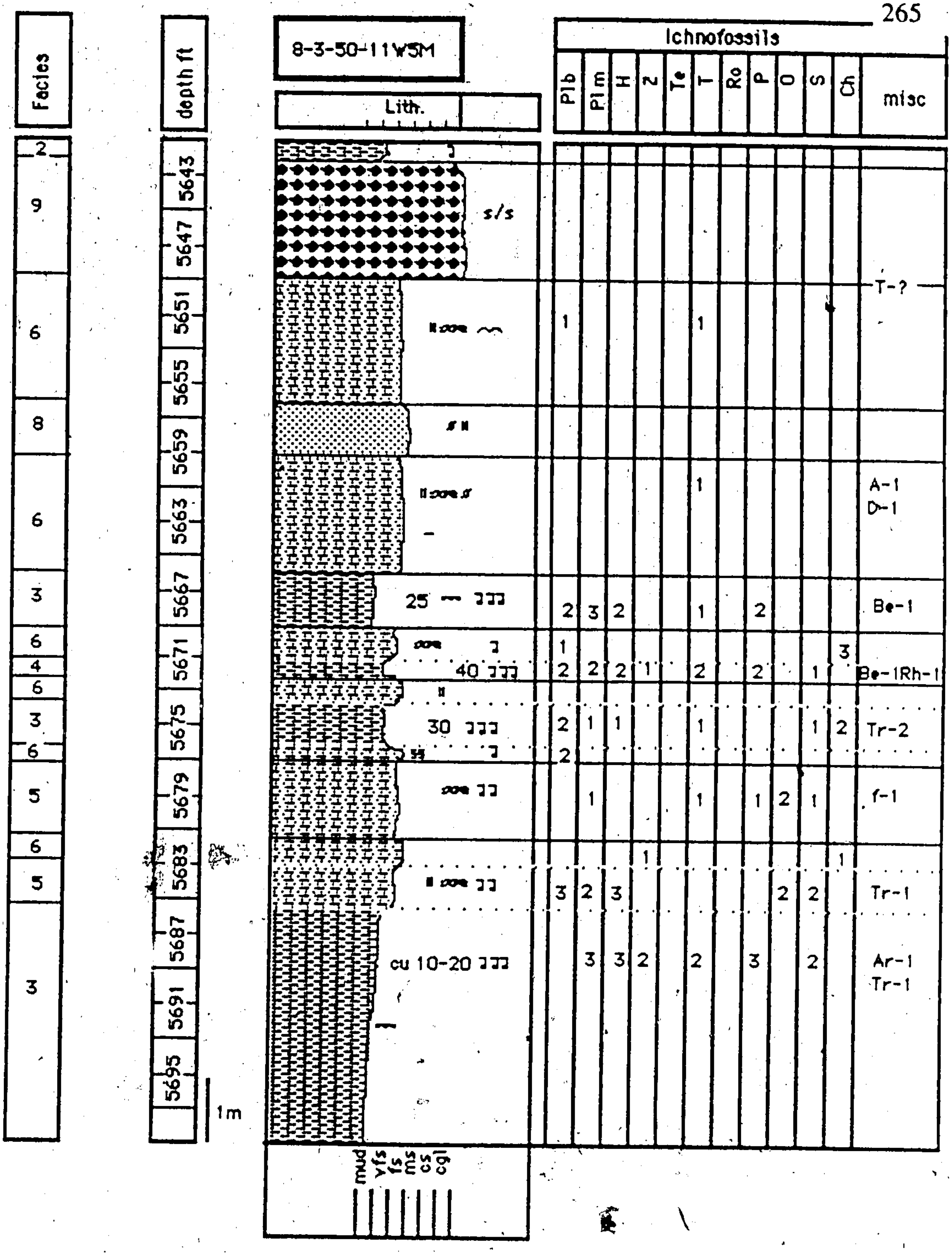
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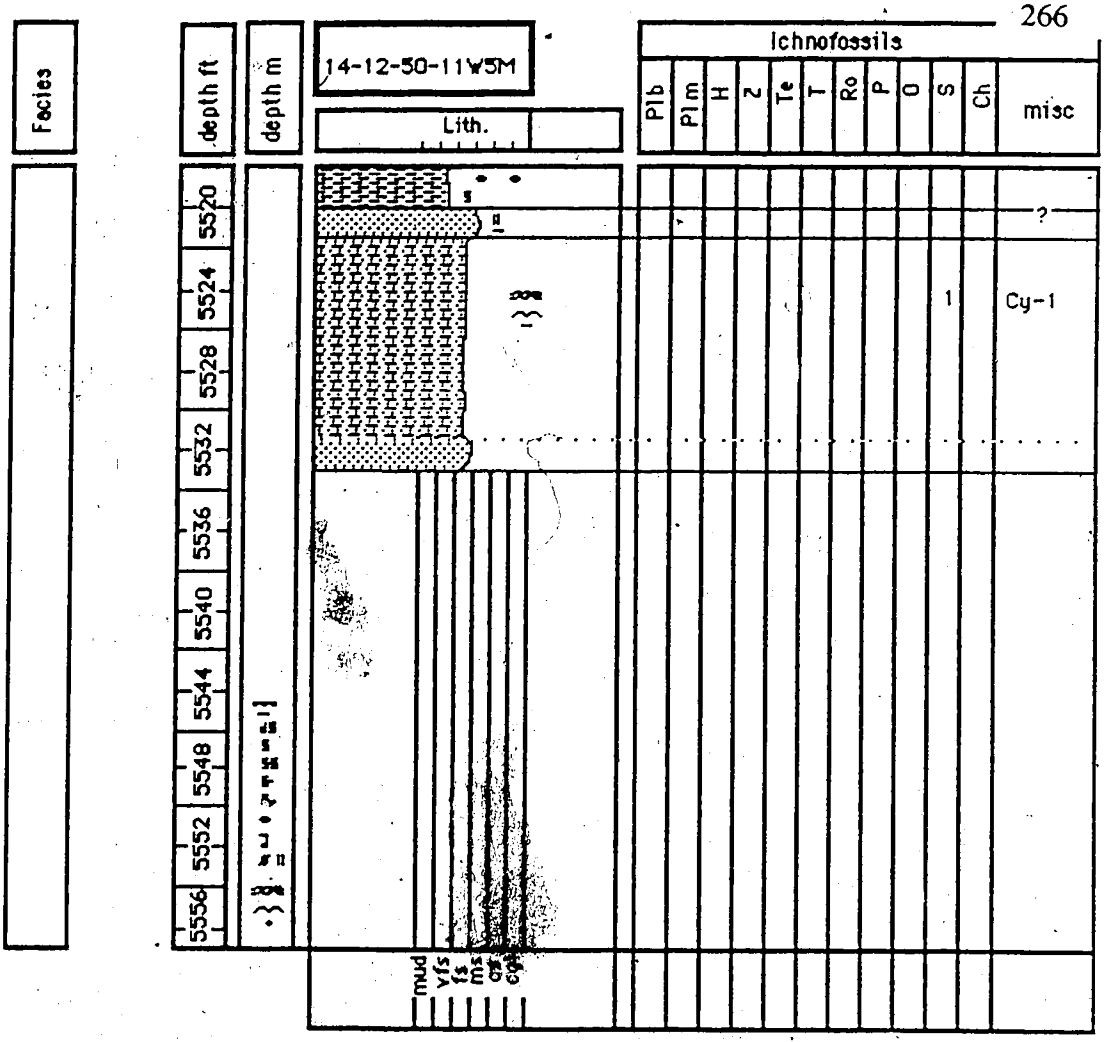
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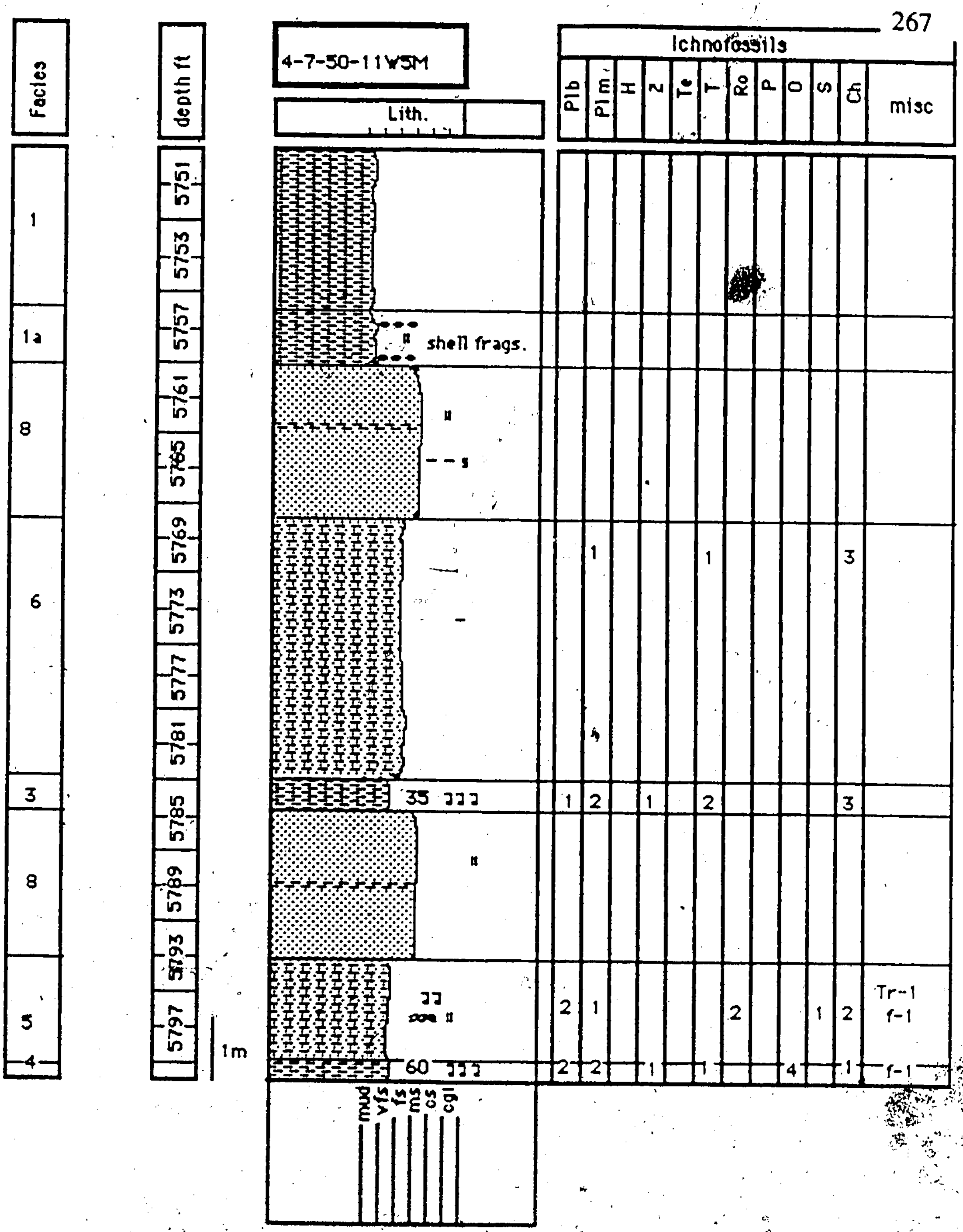
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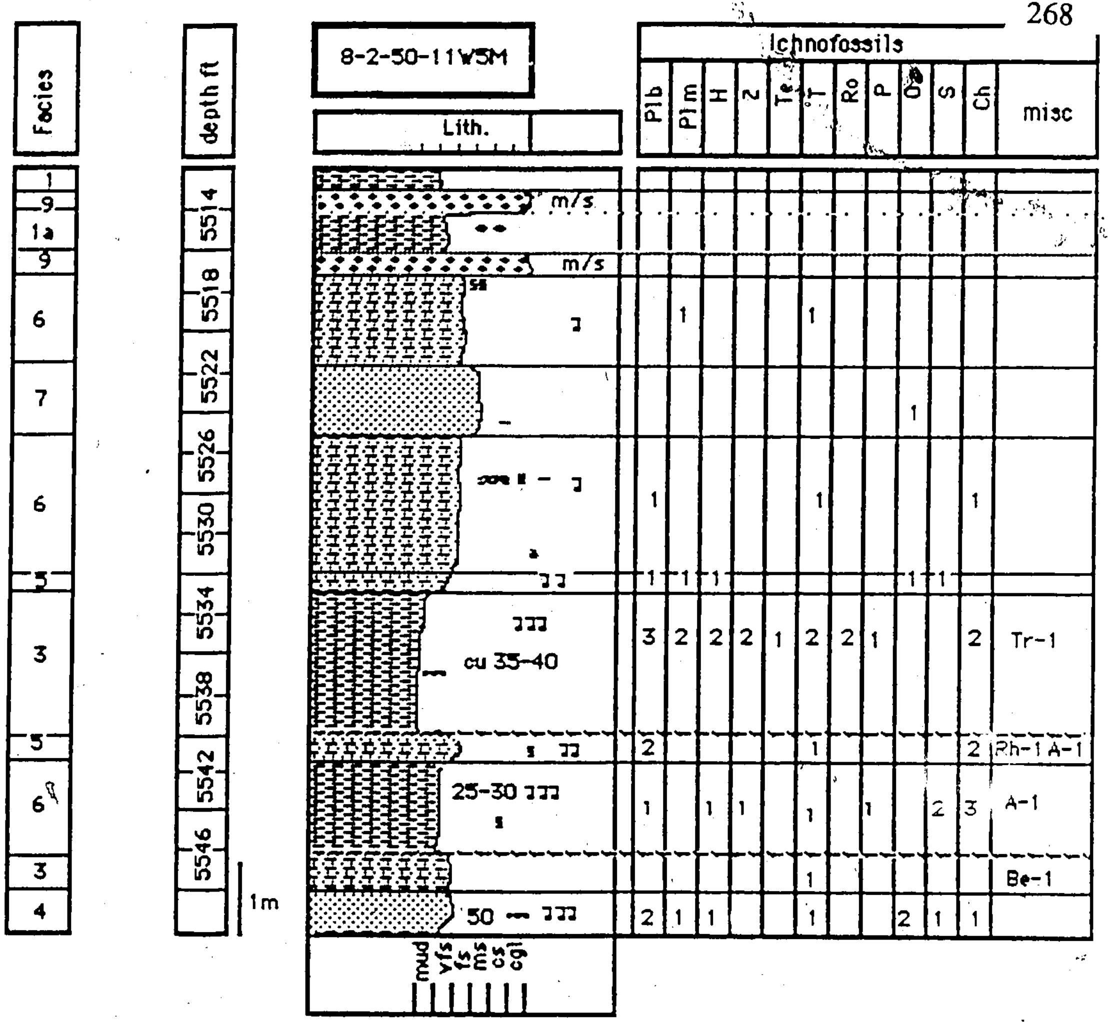
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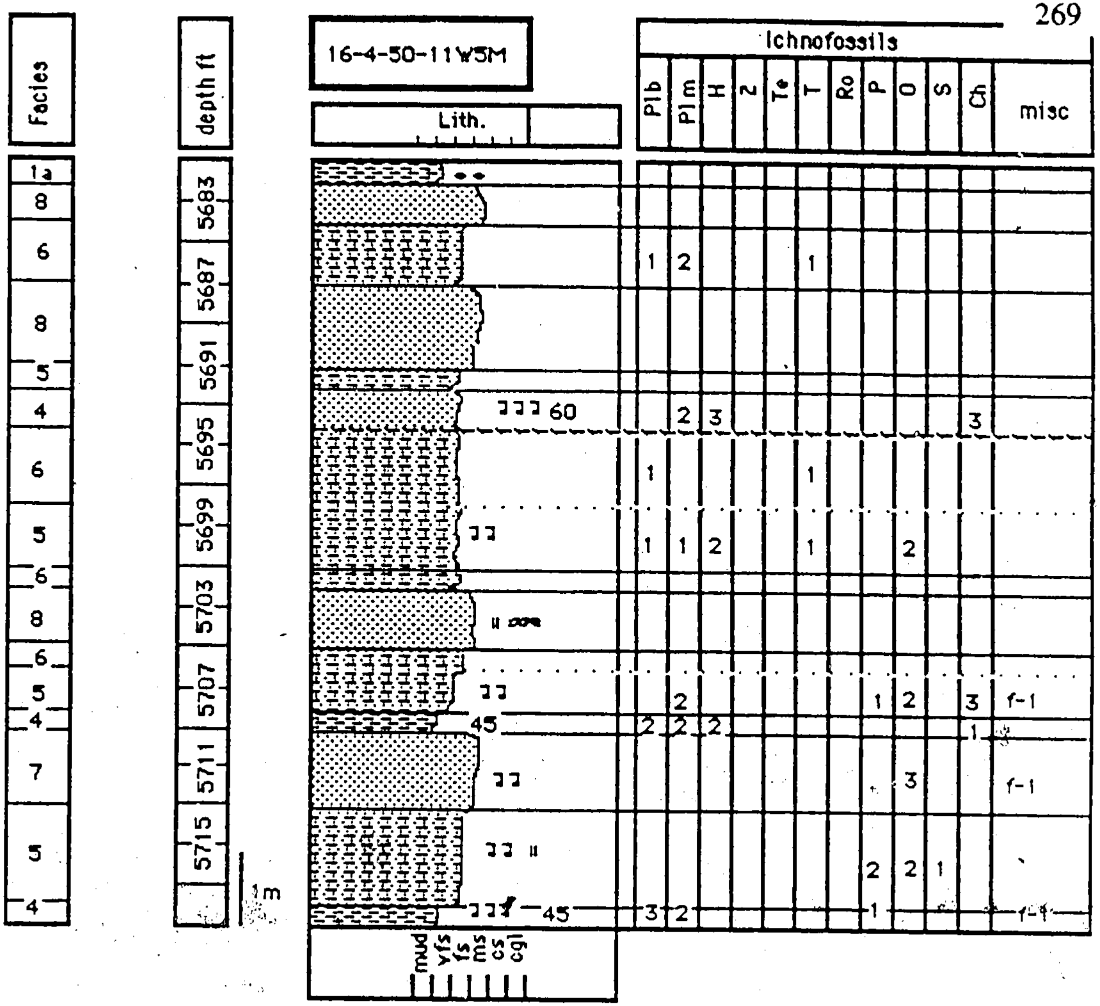
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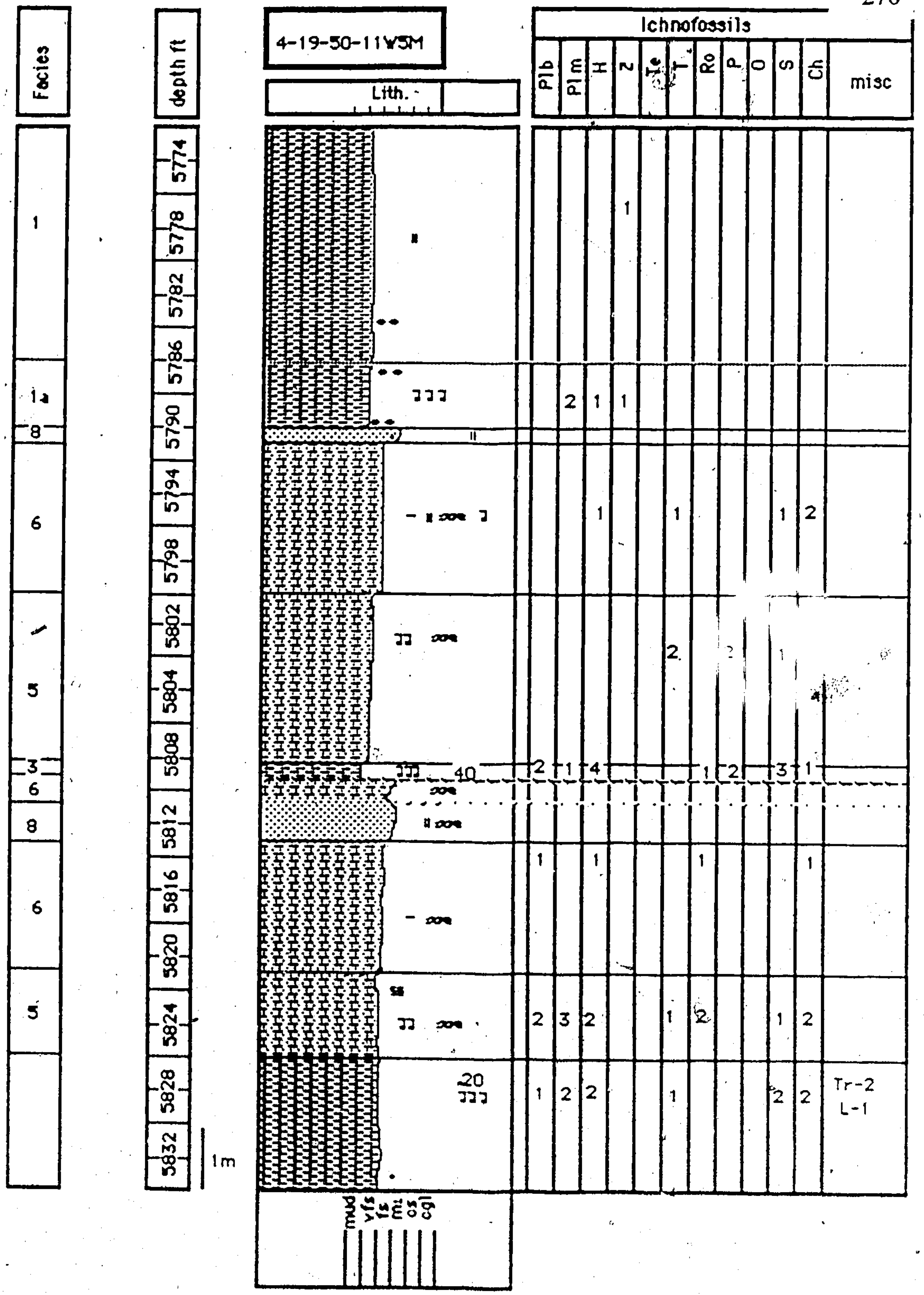
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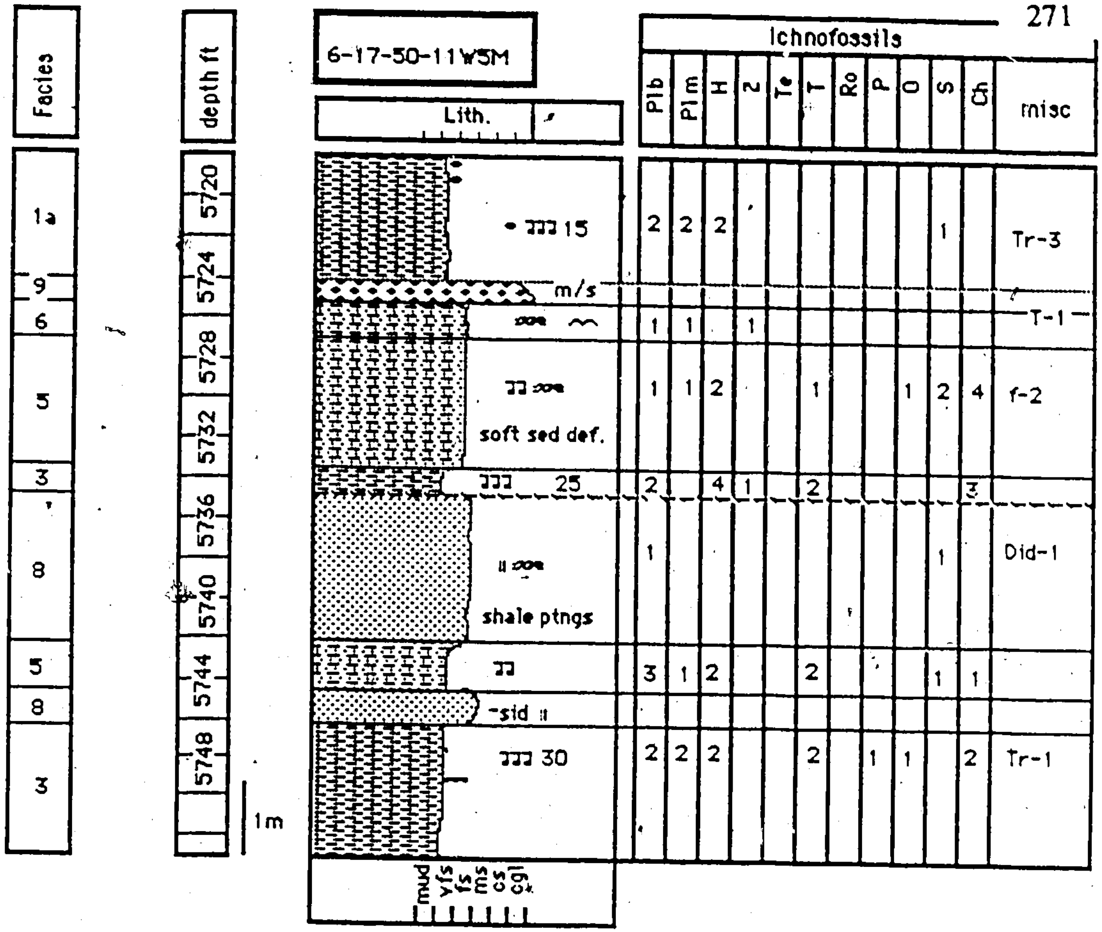
Facies
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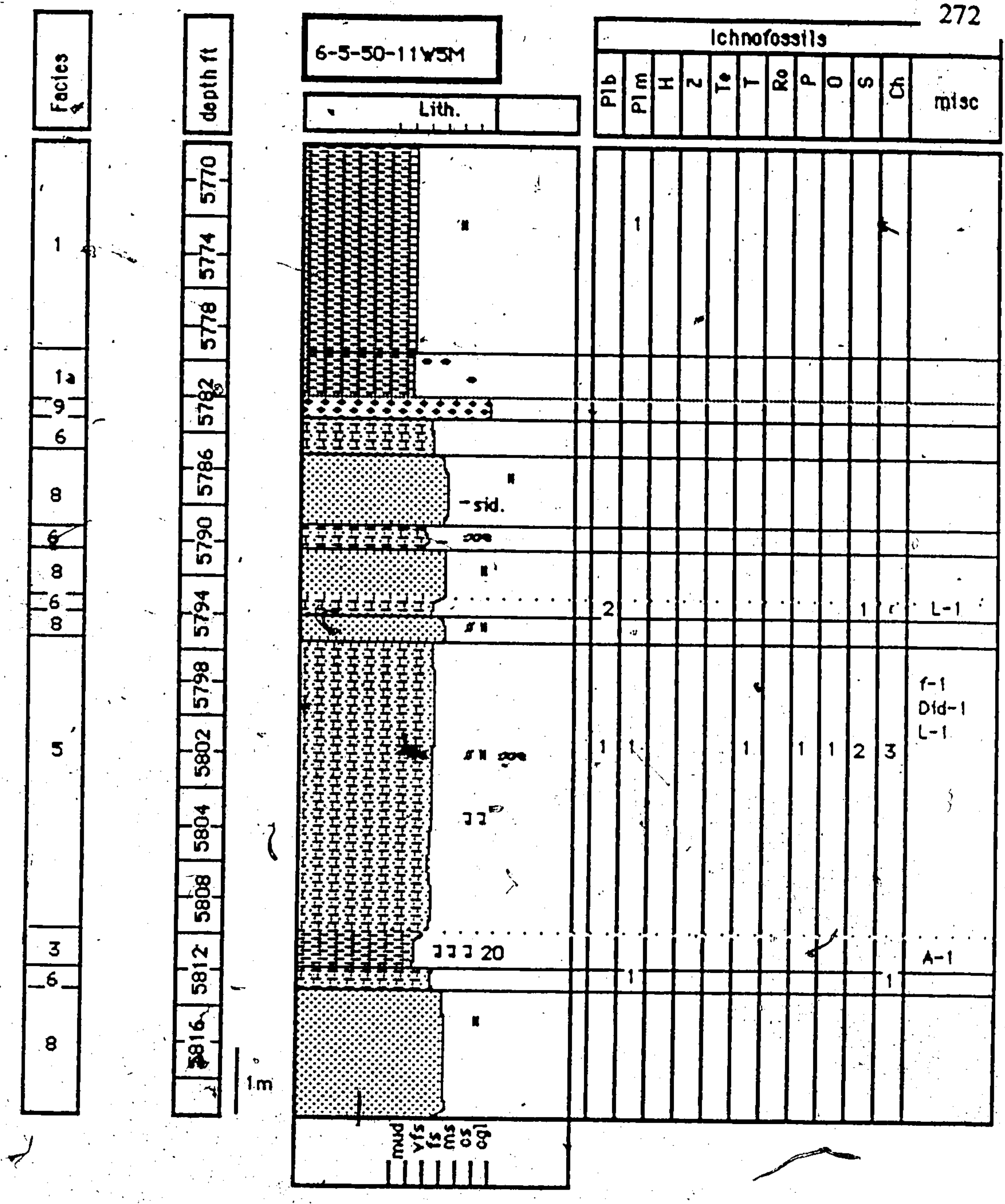
Facies
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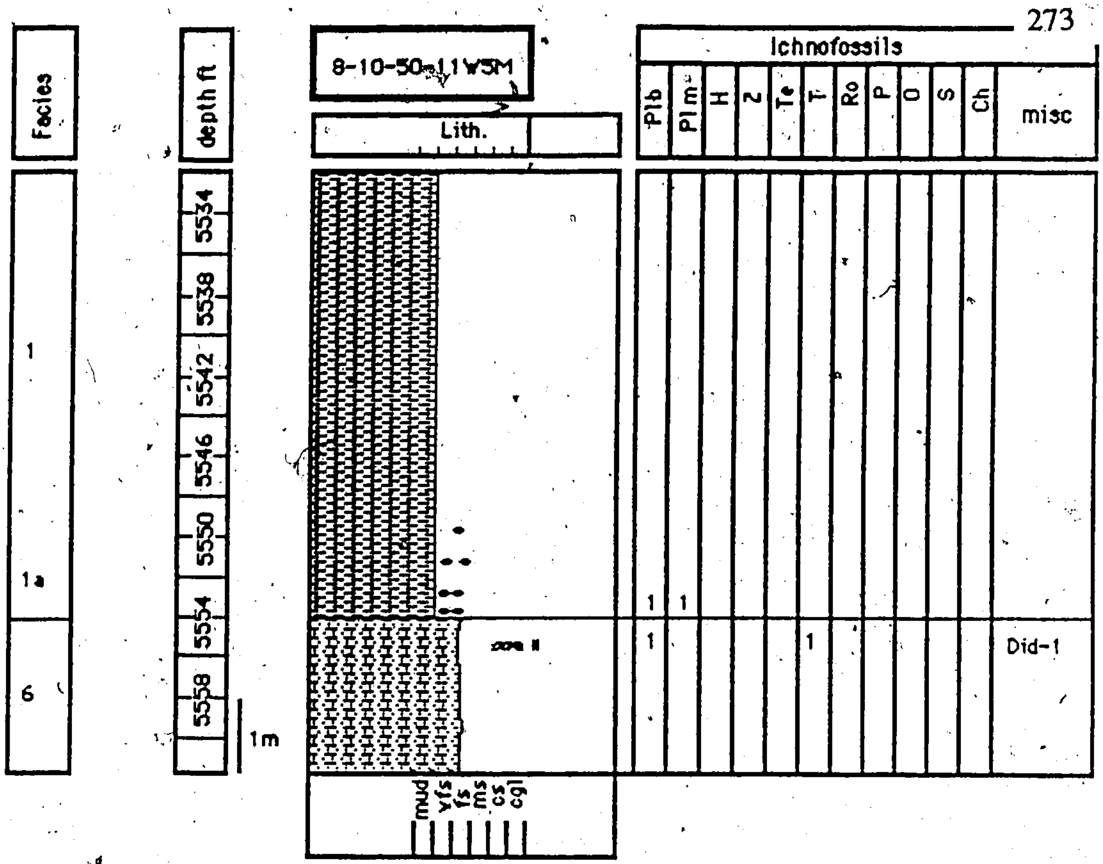
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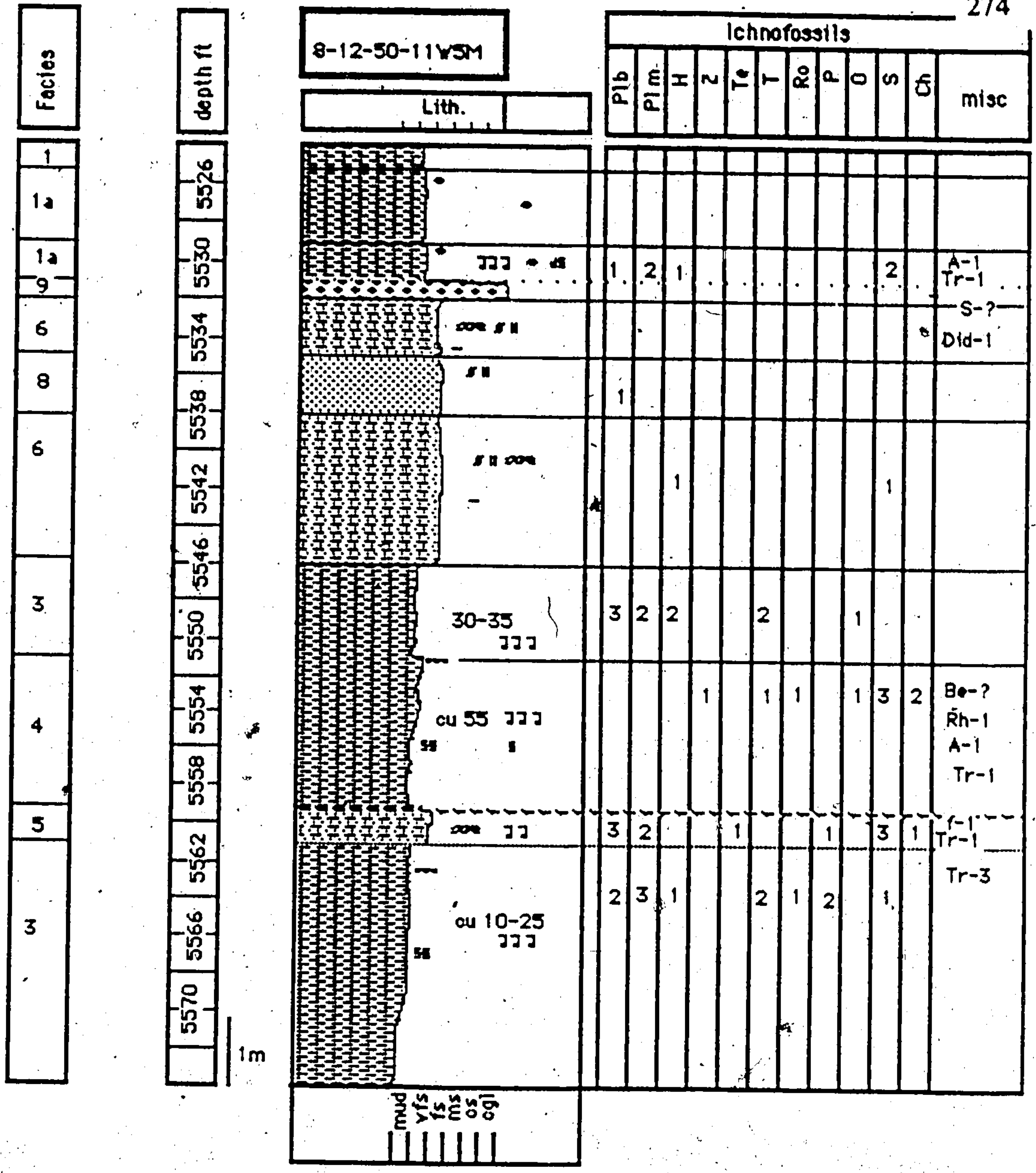
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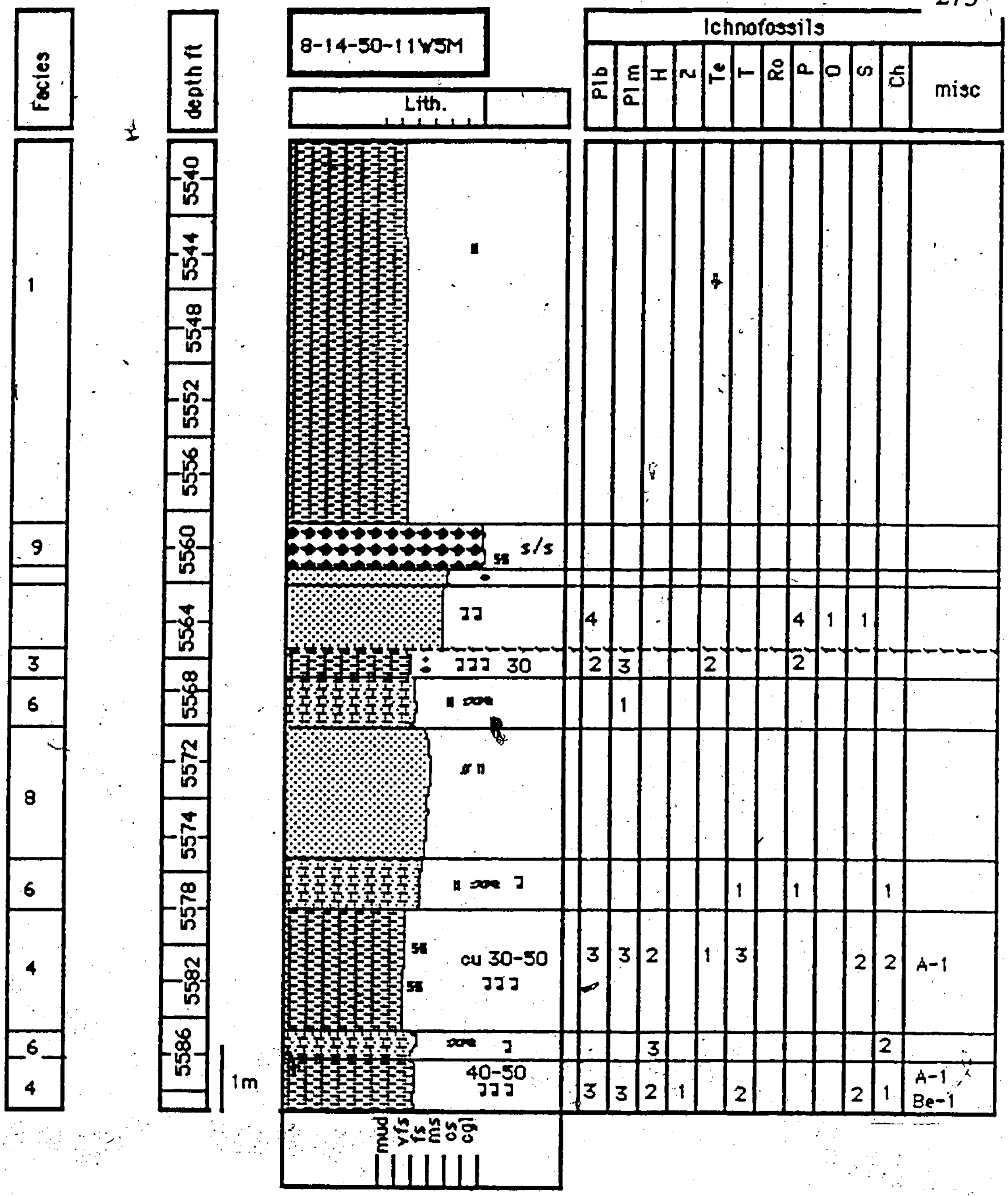
Facies
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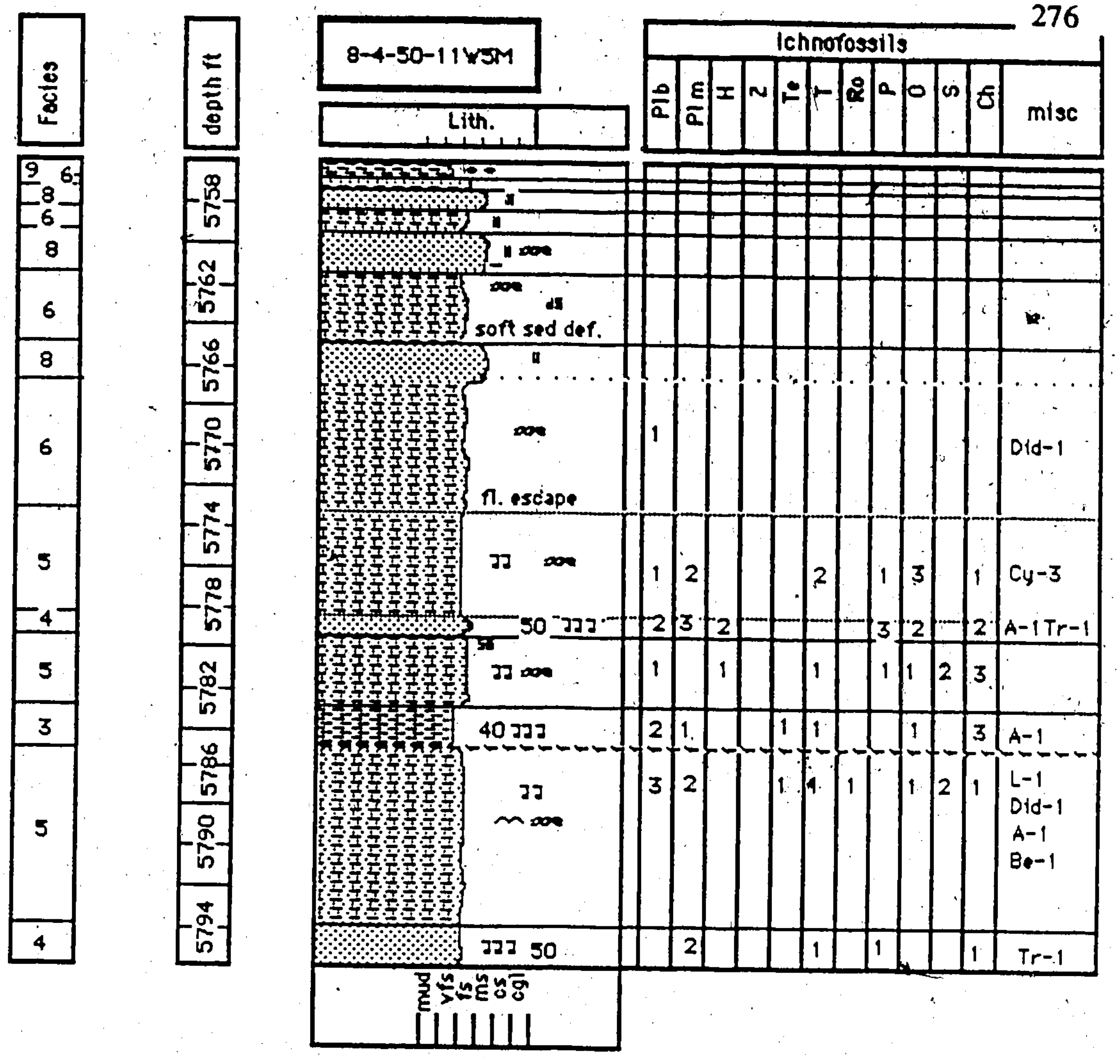
Facies
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2 3 2 3 2 2 A-1 Tr-1
1 1 1 1 1 2 3
40
2 1 1 1 1 3 A-1
3 2 1 4 1 1 2 1 L-1 Did-1 A-1 Be-1
50
2 1 1 1 Tr-1
mud
vfs
fs
ms
cs
cgl

◆◆◆	pebble conglomerate
⁘	sandstone
▤	interbedded sandstone and mudstone
▦	mudstone
┅	siltstone
⁙	granule size conglomerate

—	thin sharp-based sandstone bed
-	shale clasts
ds	dispersed siderite
s	siderite nodule
ss	siderite band
s▸	gritty siderite band
ᴫ	pyrite
●	chert pebbles
ɔ	bioturbation
∥	parallel lamination
∾	wave ripples
〜	wavy bedding
◡	load structures
•	sand grains
⁄	gently inclined lamination