DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2004/89

Sedimentology of the Upper Maastrichtian chalk, Danish Central Graben

M-10X (Dan Field), E-5X (Tyra SE Field)
Facies and core logs

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A contribution to EFP-2001 (1313/01-0001)

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Abstract

Based on detailed logs presented here at 1:10, the cored Upper Maastrichtian succession of the M-10X (Dan Field) and E-5X (Tyra SE Field) wells in the southern Danish Central Graben is subdivided into eight lithofacies and five ichnofabrics. The dominant bioturbated or laminated chalk mudstones and subordinate sparse skeletal wackestones are largely the result of pelagic carbonate production, sedimented by suspension settling and small volume, low density turbidity currents. Evidence of winnowing/reduced sedimentation rates is yielded by rare incipient hardgrounds; a well-developed mature hardground profile is developed at the Cretaceous–Danian boundary (the "Maastrichtian hardground"). Rare marl laminae are recorded and a discrete marly chalk bed associated with an interval of fine-grained skeletal chalk wackestones near the top of the Maastrichtian is recognised in both wells. Comparison between the two wells demonstrates that the m-scale laminated–bioturbated chalk cycles described from the Dan Field area are both stratigraphically and areally restricted; this has implications for both cyclostratigraphic correlation and reconstruction of depositional environments and Late Maastrichtian evolution of the Danish Central Graben.

Introduction

The two key wells selected for detailed analysis in this project were the M-10X well from the Dan Field and the E-5X well from the Tyra SE Field, both from the Salt Dome Province of the Danish Central Graben (Fig. 1). The aim of the project was to improve the understanding and resolution of the stratigraphy and palaeoenvironmental evolution within the most important reservoir level in the Upper Cretaceous chalk of the Danish Central Graben. The two key wells were chosen as they provide full cored sections through the Upper Maastrichtian reservoir chalks in two different structural settings in the southern Danish Central Graben. The two wells have also been included in previous sedimentological, stratigraphic and geochemical studies (Kristensen *et al.* 1995; Toft *et al.* 1996; Scholle *et al.* 1998; Damholt 2003; Damholt & Surlyk, in press) and all available data indicated that they provide complete stratigraphic sections through the relevant interval and do not include major resedimented chalk intervals that would complicate environmental and stratigraphic studies.

The cored sections were sampled (at roughly 1 m intervals) for palaeontological, palynofacies and isotopic investigations and were also studied sedimentologically, the aim being to provide detailed sedimentological logs that would aid interpretation of both short-term and long-term palaeoecological trends. The aim of this report, therefore, is to present the detailed core observations in the form of core logs (Appendices 1, 2), to describe the chalk sections in terms of lithofacies and to briefly discuss the sedimentological evolution of the two wells.

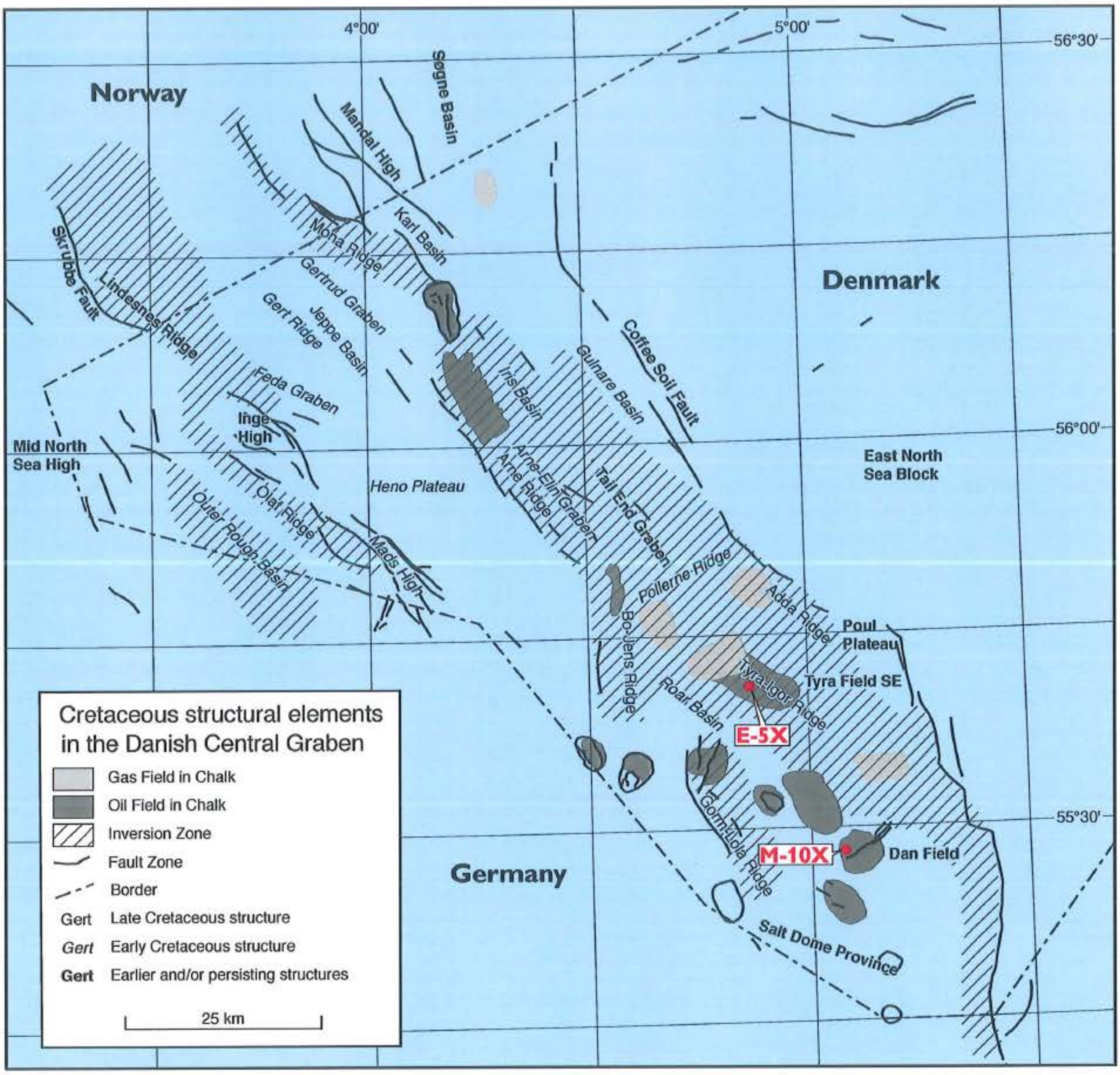


Fig. 1. Late Cretaceous structural framework of the Danish Central Graben showing the position of the M-10X and E-5X wells within the Dan and Tyra SE Fields, respectively.

Methods and log presentation

The slabbed cores were logged at a scale of 1:5, using a modified "Joint Chalk Research" format. Core preservation is variable, given the ancestry of these two wells. Since many core boxes contain fragmented and often disorganised fragments, the slabbed sections were carefully re-ordered on a wooden frame prior to logging, based on the core markings and core photographs. Unslabbed intervals and intervals of chaotic rubble (either due to original coring problems or to subsequent excessive plugging/sampling) were not included in the core logs. Other gaps on the logs relate to preserved samples and intervals removed for various technical studies.

Important criteria noted rigorously during logging were lithology (chalk mudstone, wackestone etc.), nature of grains, sedimentary structures, bioturbation (intensity, type), fractures (intensity, type), diagenetic features (stylolites, hardened layers etc.) together with location of polished slabs (M-10X) and samples (biostratigraphic/palynofacies/isotopic samples, poroperm plugs for reference). Sedimentary and biogenic features are enhanced by natural oil staining through much of the cored sections, although staining is variable in the lower levels (in the transition zone) and in the upper levels of E-5X, above the GOC. Treatment of slabbed sections with oil to enhance structures was thus not necessary.

A naturalistic, rather than schematic, logging style was adopted in order to derive as much information as possible from lithologically very uniform sections. The aim with this logging method is to provide a textural view of the section and a means to qualitatively evaluate variation in fabric/textures (i.e bioturbation intensity) that would be poorly reflected by a schematic log. It is acknowledged, however, that such a log must be treated with some caution since variation in texture may be as much a function of variation in hydrocarbon staining, and thus visibility of fabrics, as it is a primary sedimentological feature. The logs are presented in Appendices 1 and 2 at a scale of *c.* 1:10; the structures and fractures columns are redrawn accurately from original 1:5 core logs.

Stratigraphy

The cored sections studied in this project span the upper Tor Formation (Upper Maastrichtian, part of the Chalk 5 unit of Lieberkind *et al.* 1982) and the lowermost levels of the Danian Ekofisk Formation (Chalk 6 unit of Lieberkind *et al.* 1982). As shown in Figs 2 and 3, the M-10X cored section extends stratigraphically deeper into the Tor Formation than the E-5X cored section. The former extends from the nannofossil UC19 Zone through the UC20 a–d subzones of the Late Maastrichtian; the equivalent dinoflagellate and planktonic foraminifer zones are indicated on Figs 2 and 3 and the integrated dataset indicates a continuous record through the late Late Maastrichtian (see Ineson *et al.* 2004a, this study). The "Maastrichtian hardground" at top Tor Formation is succeeded by middle Danian (NNTp2E nannofossil Zone) strata indicating a significant hiatus at the Cretaceous/Danian boundary (see Lassen & Rasmussen 2004, this study; Schiøler 2004, this study; Sheldon 2004, this study). The cored Maastrichtian section in M-10X is 219 ft (66.25 m) thick; the lowermost 6 ft of the Danian section was logged and sampled in this project.

As noted above, the E-5X cored section does not extend stratigraphically so low as in M-10X – the base of the section lies within the UC20b nannofossil subzone (Pde dinoflagellate Zone; Fig.3). The cored Upper Maastrichtian section also appears stratigraphically complete, within the attainable biostratigraphic resolution. Indeed, the thickness of the biozones is bradly comparable between the two wells, suggesting similar sedimentation rates although an exception is noted in the upper levels where the uppermost biozones (UC20d, Pgr, FCS 23b) are significantly thinner in the E-5X well; furthermore, dinoflagellate quantitative data indicate that this section may be incomplete, although poor core coverage in the lower half of the Pgr dinoflagellate Zone precludes confirmation. A hiatus comparable to that in M-10X is demonstrable at the Maastrichtian/Danian boundary in E-5X i.e. the UC20d nannofossil subzone succeeded by middle Danian, NNTp2E nannofossil Zone. The cored Upper Maastrichtian section in E-5X is 156 ft thick (47.53 m); the lowermost 19 ft of the Danian section was logged and sampled in this project.

In general, the two sections are stratigraphically comparable and sedimentological, palaeoecological and isotopic observations can be compared with confidence in the stratigraphic framework.

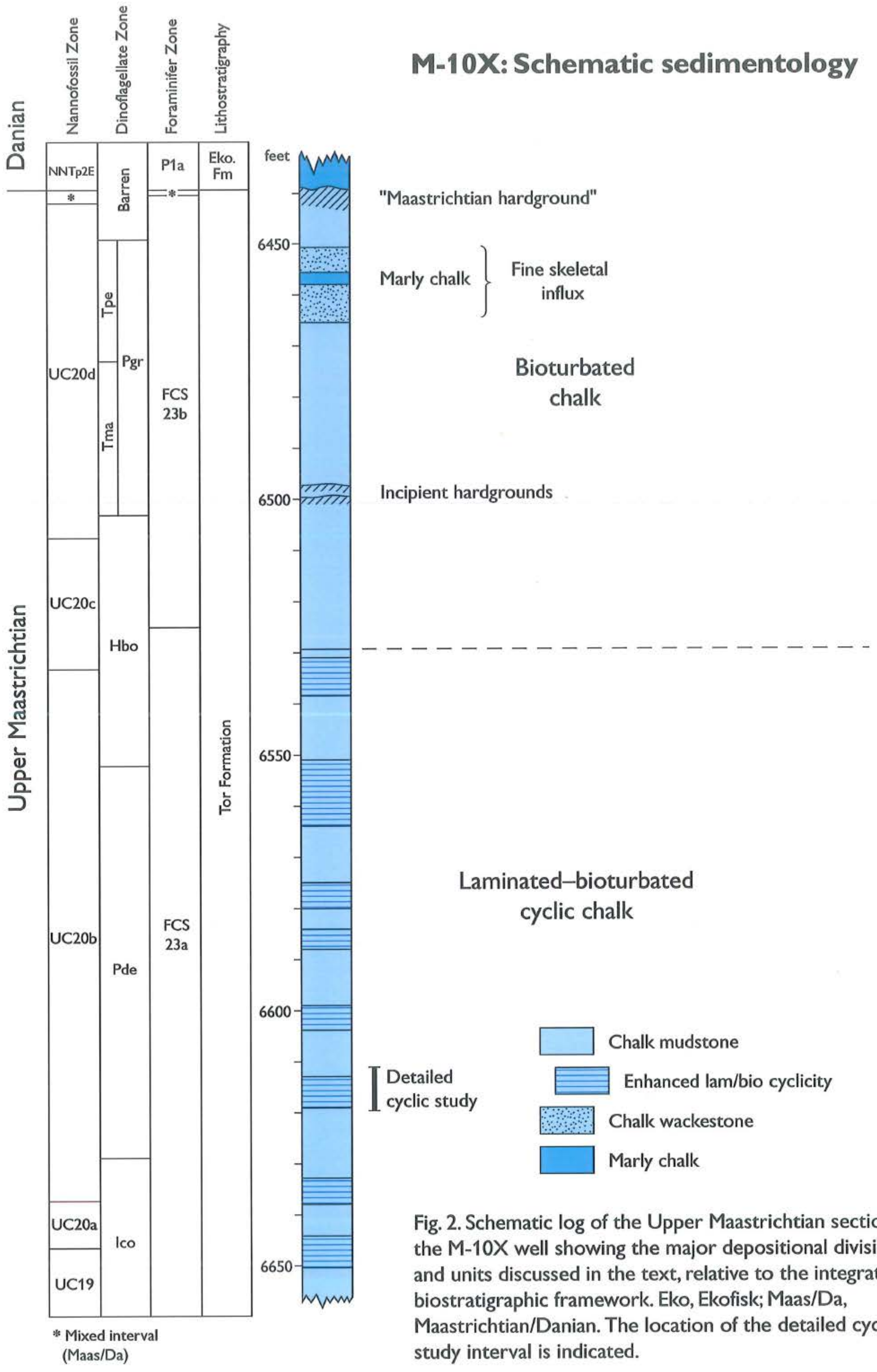


Fig. 2. Schematic log of the Upper Maastrichtian section in the M-10X well showing the major depositional divisions and units discussed in the text, relative to the integrated biostratigraphic framework. Eko, Ekofisk; Maas/Da, Maastrichtian/Danian. The location of the detailed cyclic study interval is indicated.

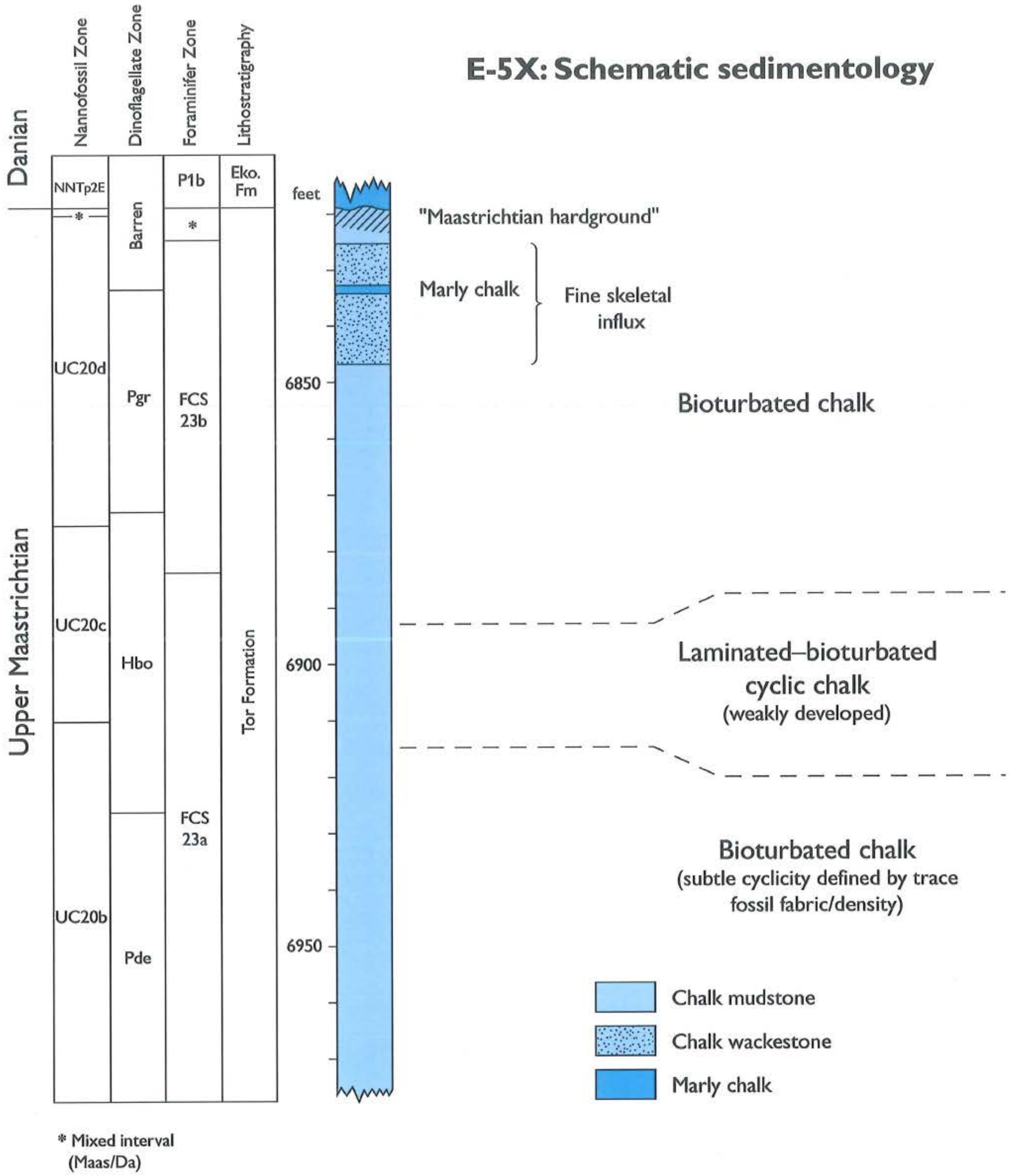


Fig. 3. Schematic log of the Upper Maastrichtian section in the E-5X well showing the major depositional divisions and units discussed in the text, relative to the integrated biostratigraphic framework. Eko, Ekofisk; Maas/Da, Maastrichtian/Danian.

Lithofacies

Overtly, the Upper Maastrichtian Tor Formation of the M-10X and E-5X wells is a homogeneous chalk pile, showing little evidence of the dynamic processes of wholescale resedimentation known from the formation further north in the Central Graben (e.g. Watts *et al.* 1980; Surlyk *et al.* 2003). Indeed, the prominent feature of these cored sections from the southern Danish Central Graben is biogenic reworking of "pelagic" chalks, and evidence of large-scale resedimentation processes is lacking.

Detailed logging, however, reveals a range of lithofacies that together outline broad regional depositional trends and form the framework for detailed palaeoecological interpretation. Eight lithofacies are recognised, combining both lithological criteria (texture, grain size, clay content) and sedimentary structures (lamination, bioturbation etc.). These are illustrated on the core logs (Appendices 1, 2) and are described briefly below. For recent detailed facies descriptions of Upper Maastrichtian chalk, particularly from the Dan Field area, the reader is referred to Damholt (2003) and Damholt & Surlyk (in press).

1. Laminated chalk mudstone

Description. This lithofacies is dominated by a lime mudstone fabric; local concentrations of coarse silt – very fine sand grade skeletal material (foraminifers, brachiopod/bivalve fragments etc.) in certain laminae may elevate the fabric locally to a sparse wackestone category. The diagnostic feature of the lithofacies is the presence of diffuse parallel lamination, defined by slight variations in porosity and thus degree of oil staining (Fig. 4). The more porous, more heavily stained laminae are up to a few mm thick and although commonly extending across the full core width, may wedge out laterally, such laminae are defined locally by weak concentrations of fine skeletal detritus. Detailed descriptions of this laminated facies, both macroscopically and microscopically, are presented by Damholt (2003) and Damholt & Surlyk (in press). Isolated burrows (typically *Chondrites*) are locally seen to truncate the diffuse lamination (Fig. 4; see ichnofabric A, below).

The laminated facies forms units (beds) ranging from a few cm to 50 cm thick, typically 10–20 cm thick, and are bounded by thoroughly bioturbated chalks (lithofacies 3) or by weakly/locally laminated chalks (lithofacies 2). Where non-stylolitic, the boundaries are commonly gradational (see Appendix 1, 6533–6531 ft).

Occurrence. This facies is common in the lower half of the Upper Maastrichtian cored section of M-10X (Fig. 2), forming about 13% of the preserved cored section in this interval. Within the uppermost Maastrchtian (Fig. 2, FCS 23b), such well-laminated chalks are not recognised. In E-5X, the facies is very rare, forming only 1% of the preserved core.

Interpretation. The origin of these laminated chalks, in tems of process sedimentology, has been discussed in detail by Damholt (2003) and Damholt & Surlyk (in press). These workers interpreted the lamination to reflect an alternation of pelagic (less porous) and turbiditic (more porous) deposits, individual porous laminae recording the depositional input of a

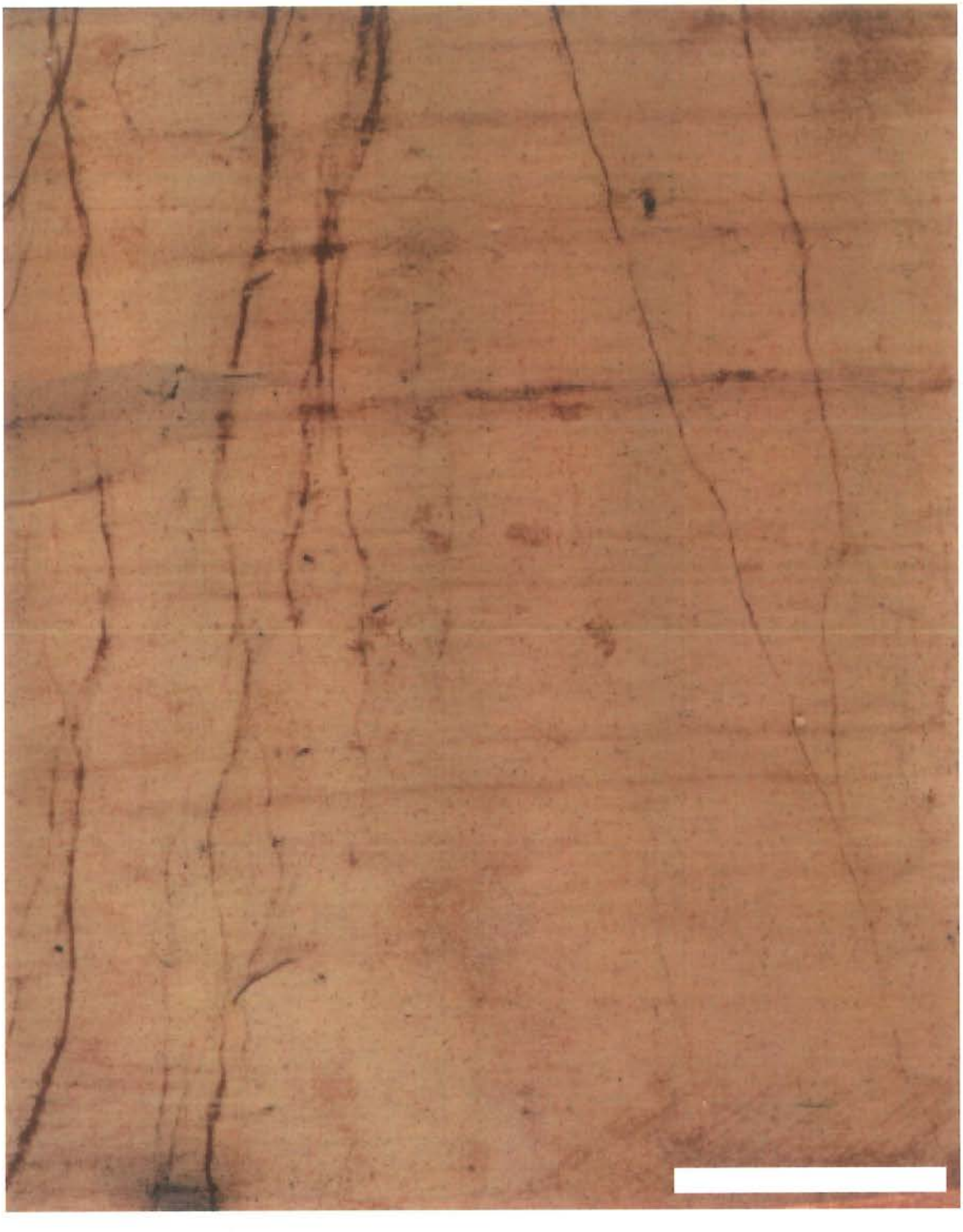


Fig. 4. Chalk mudstone (scanned polished surface) showing diffuse lamination defined by oil staining picking out weak porosity contrasts between laminae. Note truncation of the lamination by oval burrow demonstrating the primary nature of the lamination. Lithofacies 1 (ichnofabric A1), M-10X, 6635 ft 6 in, slab no. 291. Scale bar is 10 mm.

single small-volume dilute turbidity current into a region receiving a background rain of pelagic carbonate. Detailed petrographic study has not been undertaken here and the process interpretation of Damholt & Surlyk (in press) is followed. The nature of the factors controlling preservation of these subtle stuctures is discussed elswhere (see Ineson *et al.* 2004b, c, this study) but has been interpreted to have resulted from dysoxic–anoxic conditions on the sea floor (Damholt 2003; Damholt & Surlyk, in press) . The scarcity of laminated chalks in the E-5X well, at stratigraphic levels characterised by lamination in M-10X, is noteworthy and reflects on the nature of the controlling mechanisms (Ineson *et al.* 2004b, c, this study).

2. Weakly/locally laminated chalk mudstone

Description. This lithofacies spans the transition between well-laminated chalk mudstones (lithofacies 1) and thoroughly bioturbated chalk mudstones that lack or show only rare vestiges of lamination. It includes therefore a range of fabrics from chalks showing poorly defined, yet apparently persistent lamination to chalks showing abundant biogenic fabrics yet with local preservation of "islands" of primary lamination. The lithofacies also includes intervals of thinly alternating burrowed and laminated chalks, on a scale of a few centimetres.

The gross lithology is identical to that of lithofacies 1 – a lime mudstone fabric containing up to an estimated 5% of coarse silt – very fine sand grade skeletal grains. The lamination, where preserved, is comparable to that described under lithofacies 1, although more commonly disrupted by bioturbation in this facies. The trace fossil assemblage is typically low in diversity, being restricted to lower middle / deep tier forms (*Zoophycos, Chondrites*) although locally laminated fabrics are observed in association with more diverse assemblages, including middle tier forms such as *Taenidium* and *Planolites*, with rare occurrences of *Thalassinoides* and ?*Asterosoma* (see ichnofabric A1, below). The facies has gradational boundaries (where not stylolitic) with Lithofacies 1 and 3.

Occurrence. In M-10X, lithofacies 2 forms 36% of the preserved core in the lower half of the cored section and although well-defined laminated–bioturbated alternations are represented at certain levels (see Fig. 2), this intermediate facies is particularly characteristic of the intervening intervals and volumetrically is more common than the well-laminated lithofacies 1. In E-5X, this facies is the only laminated facies recognised – lithofacies 1 is not represented. It forms about 8% of the Maastrichtian section, but is mainly present in the interval 6915–6893 ft (Fig. 3; see Appendix 2).

Interpretation. The facies clearly accumulated under conditions of more varaible sea-floor oxygenation than either lithofacies 1 or lithofacies 3 (see below). The facies shows two common patterns. **1**. The discontinuous or patchy lamination is suggestive of transitional (dysoxic) conditions under which a limited infauna could operate. It should be noted that this end-member does not represent an anoxic facies development that was subsequently penetrated by deep tier infaunal organisms since lamination is commonly preserved locally within a vague burrow-mottled fabric indicative of shallow tier forms. However, conditions were clearly not optimal as the depositional fabric was not totally destroyed prior to burial and re-bioturbation locally by intermediate–deep tier forms. **2**. The alternation of burrowed chalks and laminated chalks (with rare burrows) on a scale of a few centimetres is, in contrast, indicative of fluctuating conditions on a relatively short time frame between dysoxic and oxic. Thus, laminated beds, deposited under poorly oxygenated conditions, were subsequently burrowed down to a certain level during succeeding ventilated conditions. Such a pattern may be interpreted in terms of event beds, i.e. rapid sedimentation of thin laminated beds followed by bioturbation of the surficial layer, but the gradational nature of both bases and tops of thin laminated beds suggests that fluctuating oxygen conditions were more likely responsible.

3. Bioturbated chalk mudstone

Description. In common with lithofacies 1 and 2, the chalks of this lithofacies comprise lime mudstones with a scatter of coarse silt – very fine sand grade skeletal grains (visual estimate < 5%), typically foraminifers, inoceramid prisms and fragmented thin-shelled bivalves/ostracods. Small (up to 1 cm) brachiopods are observed locally. Where visible, skeletal grains are typically dispersed randomly (Fig. 5) but may be concentrated in burrow fills (*Planolites*).

Lamination is rarely observed in this facies which is characterised by bioturbation. A range of ichnofabrics are present, from bio-mottled with scarce definable trace fossils (typically *Chondrites* and/or *Zoophycos*) to complex ichnofabrics containing a range of trace fossils, commonly dominated by *Zoophycos*. The range of ichnofabrics, and their implications, are discussed below.

Occurrence. This facies forms nearly two-thirds of the cored Upper Maastrichtian section in M-10X, and particularly dominates the upper levels of the section (Fig. 2); it forms nearly 80% of the preserved core section above 6530 ft. The dominance of this facies is even more marked in E-5X, where bioturbated chalk mudstones form nearly 90% of the cored Upper Maastrichtian section (Fig. 3).

Interpretation. Since biogenic fabrics mask primary depositional features in this facies, the nature of the depositional process is a matter of conjecture. Given the intimate alternation of this facies with the laminated chalks (lithofacies 1) and, in particular, the transitional facies (lithofacies 2) in which "windows" of primary lamination are visible, a comparable depositional process is deemed likely, at least in the lower part of the section where lamination is in evidence. Following Damholt (2003) and Damholt & Surlyk (in press), therefore, the bioturbated chalk mudtones are attributed primarily to an intimate interlamination of turbiditic and pelagic chalk mudstones, the record of which processes has been lost due to comprehensive bioturbation.

The ubiquitous bioturbation in this facies is indicative of at least a moderate level of oxygenation of bottom waters and surficial sediments although, as discussed below, the range of ichnofabrics can be inferred to reflect varying levels of oxygenation at the sea floor (see Damholt 2003).

Fig. 5. Bioturbated chalk mudstone (Lithofacies 3, scanned polished surface) overlain (above stylolite) by bioturbated marly chalk mudstone (lithofacies 7). Note the faint mottling and random orientation of small shell fragments in the lower bed and the better definition of biogenic fabrics in the marly facies. M-10X, 6641 ft, slab no. 296. Scale bar is 10 mm.

The nature of the depositional processes responsible for the upper levels of the investigated section (above 6530 ft in M-10X) is not clear. As discussed elsewhere in this report (Ineson *et al.* 2004b), detailed palaeoecological data indicate a marked shift in the palaeoceanographic state of the basin in the late Late Maastrichtian. Uniformity of depositional processes through this change cannot be assumed; unfortunately, wholesale bioturbation of the upper levels of the section precludes comparison of depositional processes.

4. Firmground/hardground

This facies was recorded at only two stratigraphic levels in the cored Upper Maastrichtian interval in M-10X and E-5X: (a) two thin inferred firmgrounds/incipient hardgrounds in the lowermost *P.grallator* dinoflagellate Zone in the M-10X well (Fig. 2) and (b) a mature hardground developed at the top-Maastrichtian (top Tor Formation; Fig.3) boundary. These two occurrences are discribed separately.

(a) *Firmgrounds/incipient hardgrounds*. This subfacies is represented by two thin beds, each about 2–4 in. thick, ocurring at 6500 ft and 6497 ft 2 in. in M-10X. The base of the lower bed is gradational, with a gradual upward change in induration, accompanying a decrease in hydrocarbon stain (i.e. porosity) and an increase in the definition of trace fossils. The base of the upper bed is not observed due to an interval of fragmented core. The top of both beds is abrupt although the nature of the core pieces precludes confident description of the upper boundaries. In both cases, the chalk appears well-cemented, and the low level of oil staining is suggestive of low porosities. In the upper case, a marked shift in fracture pattern is observed, the cemented bed showing a few isolated irregular fractures and lacking the intense array of hairline fractures observed in the succeeding, more porous bioturbated chalks (see Appendix 1). These two beds show a distinctive biogenic fabric, a complex background mottling (possibly with *Thalassinoides* in the upper bed), superimposed by *Chondrites* and *Taenidium* (upper bed) and, most significantly, in the upper levels simple 2–3 mm diameter cylindrical, straight or rarely branched tubular structures with well-defined margins and more porous (hydrocarbon-stained) chalk infills. Although truncation of cements and/or skeletal elements cannot be demonstrated, these structures resemble borings, rather than soft-sediment burrow systems.

Interpretation. The hardened, indurated low porosity nature of these thin beds, the apparently abrupt upper surface and the presence of inferred borings suggests an origin as a firmground or incipient hardground (see Kennedy & Garrison 1975). The upper surfaces of these beds show no sign of encrustation or mineral impregnation reflecting the incipient or immature nature of these inferred omission surfaces. Their presence is significant within the uniform Upper Maastrichtian succession, however, since it is suggestive of reduced sedimentation rates or indeed a temporary cessation of chalk ooze accumulation. The implications of these surfaces at this stratigraphic level are discussed further below and elsewhere in the report (Ineson *et al.* 2004b, this study).

(b) *Top Tor Formation hardground*. As is apparent from petrophysical logs, the uppermost Tor Formation is developed as a low porosity, well-cemented layer up to 5 ft thick.

Macroscopically, the extent of this cemented zone is somewhat less – about 4 ft thick in M-10X and 2–3 ft thick in E-5X – but evidence from preservation of nannofossils confirms the continuation of marked diagentic effects of the hardground surface down to 5–6 ft below the surface itself (Sheldon 2004b, this study). The M-10X section is the more illustrative. Complex *Thalassinoides* galleries contain a skeletal/intraclastic packstone–wackestone fill (Fig. 6) that locally shows spreite indicating biogenic reworking of the burrow fill by deposit-feeding organisms. The fill is dominantly skeletal in origin but dark ?phosphoritised intraclasts are noted locally. The margins of the galleries are irregular and possibly bored in places (Fig. 6). The level of cementation increases upwards, with accompanying decrease in oil stain, and the uppermost 6–8 in. is well-cemented and shows rays of linear borings extending from the hardground surface. The surface itself is irregular, with 1–2 in. relief; small sub-circular hollows on the surface may represent bio-erosion pits. A green ?glauconitic patina is also evident locally on the hardground surface. As observed in the firmgrounds (see above), the hairline fracture networks that otherwise characterise the Maastrichtian chalk section (see Appendix 1) are scarce in this well-cemented profile, and irregular brittle fractures plugged with sparry calcite cement are more characteristic of this level. A discrete nodular flint level occurs approximately 3 ft below the top Tor Formation surface. In the E-5X well, the upper levels of the Tor Formation show similar evidence of hardground development (see Appendix 2), although the surface itself is not observed (section removed as "preserved sample"). Glauconite grains are observed within the packstone-filled *Thalassinoides* network. Localised flint nodules occur about 1 ft 6 in. and 3 ft below the boundary.

Interpretation. The complex cross-cutting *Thalassinoides* networks, the cemented and bored upper layer and the irregular, pitted, glauconite-impregnated upper surface are all features indicating that the top Tor Formation surface was a mature, evolved hardground surface, recording a protracted period of non-sedimentation at the sea floor (e.g. Kennedy & Garrison 1975). This is confirmed by the biostratigraphic data (Lassen & Rasmussen 2004, this study; Schiøler 2004, this study; Sheldon 2004, this study) indicating a marked hiatus at this surface, with a duration of at least a few hundred thousand years and possibly as much as 2 Ma. The occurrence of mixed Late Maastrichtian and early Danian faunal and floral assemblages within the upper few feet beneath the hardground surface suggests that the burrow systems remained open into Danian time, thus accumulating complex multi-generational fills.

5. Burrowed chalk wackestone/packestone

Description. As noted above, coarse silt – very fine sand grade skeletal detritus forms a notable component of the chalk mudstone facies (lithofacies 1–3) but generally forms less than 10% of the rock with the exception of isolated laminae in lithofacies 1 and 2 and burrow fills in lithofacies 3. Lithofacies 5, however, comprises discrete beds and intervals up to several feet thick in which the dominant fabric is a matrix-supported skeletal wackestone (typically 10–30% grains) with local concentrations in burrow fills that approach a skeletal packstone fabric.

Fig. 6. Bioturbated chalk mudstone (scanned polished surface), transected by *Thalassinoides* gallery filled with skeletal wackestone/packstone; note the irregular (?bored) nature of the burrow margins. About 2 ft 6 in below the "Maastrichtian hardground" surface at top Tor Formation. Lithofacies 4, M-10X, 6441 ft 6 in, slab no. 102. Scale bar is 10 mm.

The fine-grained skeletal component (foraminifers, fragments of thin-shelled bivalves/?ostracods, brachiopods and locally bryozoans) is dispersed and typically randomly oriented. Bioturbation fabric predominate (ichnofabrics analagous to those in lithofacies 3, see below) although diffuse lamination is locally preserved.

Occurrence. Although recorded locally in the lower cored levels in both wells (see Appendices 1, 2), the facies characterises an interval towards the top of the formation in both well sections within which it forms 20–30% of the section (Figs 2, 3).

Interpretation. As for lithofacies 3, the chalk wackestones are predominately wholly bioturbated, such that primary depositional processes cannot be ascertained. The presence locally of lamination resembling that of lithofacies 1 and 2 suggests that comparable processes were responsible for their deposition i.e. a combination of pelagic settling and low density, small-volume turbidity currents (Damholt 2003; Damholt & Surlyk, in press). The increase in the coarser skeletal components (albeit still in the coarse silt – very fine sand grade) may indicate slightly elevated energy levels or transport capacity or a palaeoecological change in the Danish Central Graben; the appearance of bryozoan fragments in this facies in the uppermost Maastrichtian is particularly noteworthy.

6. Slumped chalks

Description. Evidence of mass transport (slump, slides, debris flow etc.) in the cored M-10X and E-5X section is highly restricted; sedimentation in this part of the graben was dominated by relatively low energy, passive processes – pelagic settling and small-volume dilute turbidity currents. Two minor slump structures are tentatively recognised in the upper levels of the E-5X section, however, both apparently involving no more than a few tens of centimetres of sediment. The lower slump, at 6843 ft (see Appendix 2) is defined by the orientation and streaked-out nature of trace fossils and faint lamination, enhanced by stylolites, whereas the upper, at 6835 ft 6 in., is picked out by a contorted *Zoophycos* trace.

Interpretation. The minor slumps testify to local sediment instability on the Tyra SE site. It should be noted, however, that the trace fossils appear to be deformed but not displaced i.e. the slump folds are rooted and are of minor significance.

7. Marly chalks

Description. The Upper Maastrichtian chalks in E-5X and M-10X are remarkably homogeneous and pure, with only a low clay content (Scholle *et al.* 1998; Damholt & Surlyk, in press). Both clay-rich and flint horizons are notably scarce, in comparison to the succeeding Danian succession (Ekofisk Formation). A few thin clay-rich levels were noted, however, typically as isolated marlstone laminae (see below) or thin marly chalk beds up to 1–2 in. thick (Appendix 1, 6641 ft).

A discrete marly chalk interval was recorded in both wells, at 6458 ft 4 in. – 6456 ft 7 in. in M-10X and 6833–6834 ft in E-5X. It comprises bioturbated slightly marly chalk mudstone (to sparse wackestone) with (in M-10X) minor marlstone laminae forming discrete solution seams. The ichnofauna is diverse (*Zoophycos, Chondrites, Taenidium, ?Asterosoma, Planolites, Thalassinoides*) and the presence of *Thalassinoides*, often re-burrowed by *Chondrites*, is notable since this trace is uncommon overall in the bioturbated chalk mudstone facies.

Interpretation. This marly level occurs broadly at the same stratigraphic level (Figs 2, 3) and may be correlatable. It clearly indicates a pulse of increased clay dispersal into the otherwise clay-poor chalk environment, perhaps initiated by a minor sea-level or climatic perturbation. The apparent increase in trace fossil diversity in this bed relative to the chalks above and below may be in part an artefact, related to trace visibility (clay content commonly enhances trace fossil definition) but may also reflect a shift in substrate consistency due to increased clay content, favouring intermediate tier infaunal organisms.

8. Marlstones

Marlstones were recorded either as rare discrete laminae occuring isolated within homogeneous clay-poor chalks (e.g. Appendix 1, 6623 ft 4 in.) or as flasers within marly chalk intervals, such as that near the top of the cored Maastrichtian succession (see above). Lithofacies 7 and 8 are volumetrically unimportant in the Upper Maastrichtian section, forming < 1% of the preserved core section in M-10X; the implications of such rare beds/intervals are discussed under lithofacies 7.

Ichnofabrics

The degree of bioturbation in the cored Upper Maastrichtian section of the M-10X and E-5X wells ranges from absent to intense, as described above under lithofacies 1–3. Although not the subject of particular focus in this study (see Damholt 2003 for a recent ichnological study of the succession), the intensity of bioturbation (low/intermediate/high) and the ichnogenera recognised were recorded. Full diagnostic descriptions of the ichnogenera are not presented here; brief notes on the ichnogenera are given below, particularly with respect to departures from the identifications presented by Damholt (2003).

?Asterosoma
The identity of this distinctive trace fossil is not entirely clear. It comprises a light-coloured, oval (compacted) burrow, typically 3–10 mm across, that occurs within an elongate (parallel or slightly oblique to bedding) dark-coloured mantle showing irregular finger-like extensions. In some cases, two cross-sections through the central burrow are evident within a single dark mantle, suggesting a meandering central burrow system. Spreite are sometimes observed within the central burrow. Although acknowledging the absence of certain characteristic features of the ichnogenus, Damholt (2003) referred this trace to *?Asterosoma*; this tentative assignment is followed here.

Chondrites
Together with *Zoophycos*, *Chondrites* is a particularly common trace in the succession. Different sizes of *Chondrites* burrows are recorded in places. These small diameter burrows are typically well-defined, truncate all other forms and are often observed re-mining earlier burrow systems (*Thalassinoides*, *Zoophycos*). It should be noted that in this study, differentiation between *Chondrites* and *Phycosiphon* was found to be impractical and the latter ichnogenus is not recognised. This contrasts with the work of Damholt (2003).

Palaeophycus
Simple, sub-horizontal cylindrical burrows with a structureless fill and a thin dark ?organic lining (now commonly micro-stylolitic) are referred to *Palaeophycus*. Thes burrows are commonly well-defined and record a middle tier position.

Planolites
Simple, sub-horizontal, cylindrical (compacted, oval), unlined burrows are referred to *Planolites*. Commonly, the margins of these burrows are diffuse and the trace is attributed an upper middle tier position.

Taenidium
Sub-horizontal cylindrical burrows with a back-fill structured (spreite) infill are referred to *Taenidium*; a middle tier position is inferred for this trace (see also Damholt 2003).

Teichichnus
This trace is not common, nor well defined, but local diffuse spreite, apparently related to an upward migrating horizontal burrow system, are referred tentatively to this ichnogenus.

Thalassinoides

Well-defined *Thalassinoides* networks are only recognised in association with the top Tor Formation hardground (see Fig. 6 and Appendix 1), Elsewhere, large (several cm) diffuse, typically oval burrows, often with a slightly darker fill than the matrix chalk and rarely showing branching, are tentatively referred to *Thalassinoides*. These systems are cut by *Zoophycos* and their fill is commonly re-burrowed by *Chondrites*. These forms are uncommon overall but can be concentrated at certain levels (e.g. Appendix 2, 6834 ft).

Zoophycos

This ichnogenus, with *Chondrites*, dominates the succession and in places can represent the only recognisable trace, occurring in dense arrays. In contrast to the "classic" *Zoophycos* development, the cross-sections observed in core are commonly structureless or show only weak spreite and the characteristic spreited arms are only well-developed locally in large *Zoophycos* systems (e.g. Appendix 2, 6849 ft). Note that the abundance of *Zoophycos* exhibiting visible spreite has been exaggerated on the core logs to aid recognition.

Tiering

Definition and interpretation of trace fossil ichnofabrics requires an appreciation of the concept of trace fossil tiering (see Bromley 1990), viz. the relative position of individual elements of an endobenthic community with respect to the sea floor. Following Ekdale & Bromley (1991) and Damholt (2003) and confirmed by observations of burrow truncation in this study, a broad tiering model can be proposed Fig. 7).

Upper tier: Diffuse biomottling, no recognisable trace fossils

Middle tier: Vague–well-defined ichnogenera (broadly from top down) – *Planolites*, *Thalassinoides*, *Teichichnus*, *Palaeophycus*, ?*Asterosoma*, *Zoophycos*

Lower tier: *Zoophycos*, *Chondrites*

This tiering model is clearly only a general guide e.g. forms referred to *Planolites* locally cut *Zoophycos*, and *Asterosoma* and *Zoophycos* variably truncate each other. However, this broad ecological zonation provides a framework within which to analyse the varied ichnofabrics in the succession. It should be noted, however, that such a tiering profile in Fig. 7 represents a static snapshot under optimum conditions with full tier development. With progressive accumulation under such conditions, with favourable sedimentation rates, each successive tier will overprint the preceding and a complex ichnofabric will result, the lower middle and lower tier traces dominating the fabric. Under dysoxic conditions, or under conditions of rapid sedimentation, forms such as *Chondrites*, thought to be tolerant of low oxygen conditions (Bromley & Ekdale 1984), may be the sole ichnogenus and may occupy a relatively shallow position due to the steep oxygen gradient (see Bromley 1990 for a discussion of tiering under variable environmental conditions).

Five ichnofabrics are recognised in the E-5X and M-10X cored sections; these are largely comparable to those recognised by Damholt (2003). The first ichnofabric (A) represents

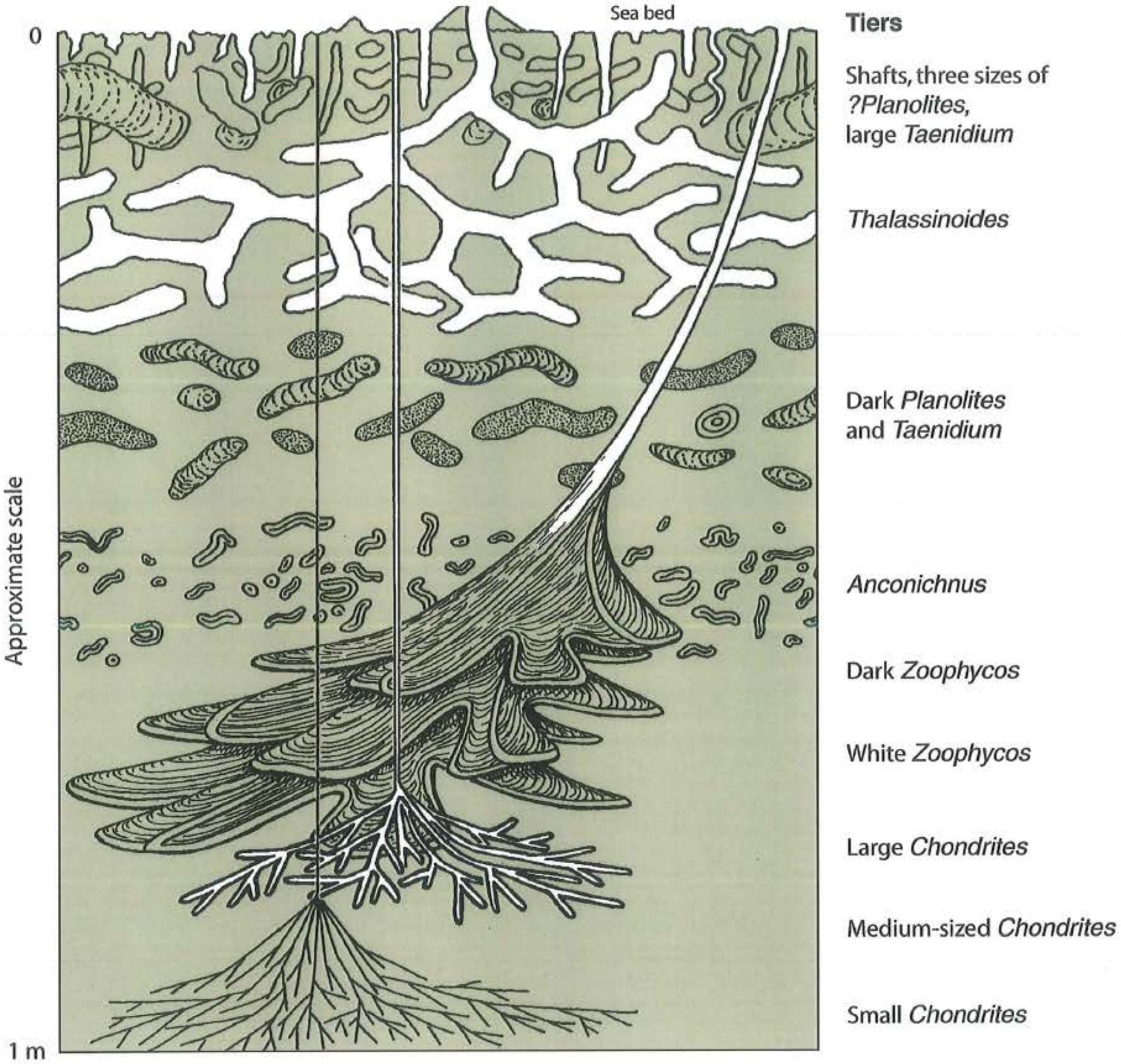


Fig. 7. Schematic 'snapshot' of a Cretaceous ooze profile showing the various trace fossil tiers at different levels beneath the sea floor. Additional ichnotaxa recognised in this study include the intermediate tier forms *Palaeophycus* and *Taenidium* and the low intermediate – deep tier *?Asterosoma*. Modified from Ekdale & Bromley (1991).

sparse "deep tier" bioturbation within laminated chalks (lithofacies 1, 2); ichnofabrics B–D are recognised within the bioturbated chalk facies (lithofacies 3) and display variation in dominance of the three tiers. Ichnofabric E is rare, representing firmground/hardground trace fossil fabrics.

Ichnofabric A

Laminated chalks of lithofacies 1 show a low bioturbation intensity, being restricted to rare *Chondrites* traces; this ichnofabric is equivalent to ichnofabric 1 of Damholt (2003). Preservation of the laminated structure indicates an absence of shallow tier burrowing and, as discussed by Damholt (2003), probably records poorly oxygenated conditions. The presence of *Chondrites* may reflect the tolerant nature of this organism with respect to low oxygen levels (Bromley & Ekdale 1984), or may record deep tier bioturbation folllowing amelioration of the stressed low-oxygen conditions.

Ichnofabric A1 is a variant of the above, as developed in the variably laminated/bioturbated lithofacies 2. Bioturbation density is low but vague burrow mottling and discrete *Planolites* locally disturb the lamination and *Chondrites* and *Zoophycos* are present. This fabric clearly records biogenic reworking under more oxygenated conditions than ichnofabric A. It is not always clear, however, whether this reflects bioturbation of sediment deposited under hostile bottom conditions following resumption of more oxic conditions at the sea floor (probably the case for laminated sediments truncated by *Zoophycos* and *Chondrites*) or low density shallow tier bioturbation resulting in partial destruction of the laminated fabric, suggesting transitional, dysoxic conditions at the sea floor.

Ichnofabric B

This ichnofabric is comparable to Ichnofabric 2 of Damholt (2003) and is observed in lithofacies 3 (bioturbated chalk mudstones). It comprises a faintly mottled, comprehensively bioturbated background fabric, recording thorough shallow tier bioturbation, upon which is superimposed *Chondrites* at a low density. Ichnofabric B1 is a variant of this ichnofabric in which *Chondrites* is supplemented by *Zoophycos* and rare *Planolites.*

Several possible interpretations of this fabric can be envisaged. Damholt (2003) suggested that such fabrics developed due to bioturbation of thin mudflow deposits. Such mudflow facies have not been recognised in this study. The lack of sedimentary structures (i.e. lamination) and the bio-mottled background fabric indicates thorough shallow tier biogenic reworking under oxygenated conditions. Evidence of intermediate tier bioturbation is lacking and the deep tier forms are in low density. This could be interpreted to reflect an abrupt increase in sedimentation rate, following shallow tier bioturbation, such that intermediate tier forms were unable to become established and deep tier burrows were scarce. Evidence of such abrupt changes in sedimentation rate is not recognised sedimentologically, however (see discussion in Damholt 2003 and Damholt & Surlyk, in press). It is more likely that this fabric reflects a transition between poorly oxygenated (ichnofabric A) and well-oxygenated conditions during which the surficial sediment was sufficiently aerated to support a shallow tier infauna, but a steep oxygen gradient in the underlying sediment precluded establishment of intermediate tier forms and the sediment was reserved for low density *Chondrites* and *Zoophycos* systems.

Ichnofabric C

Zoophycos is perhaps the most characteristic trace fossil of the Upper Maastrichtian section, but certain intervals show a particular concentration of these traces. The dominance of this ichnogenus often obscures associated trace fossils but the ubiquitous *Chondrites* is typically associated and the background fabric is biomottled, indicating superposition of the lower middle – deep tier forms on a thoroughly bioturbated shallow tier fabric. Although other intermediate traces are typically not in evidence, ?*Asterosoma* is commonly associated with this high density *Zoophycos* fabric and the apparent absence of other middle tier forms may be an artefact in some cases due to intense re-burrowing by *Zoophycos* at deeper levels. Taken at face value, however, this fabric appears to record an extreme variant of ichnofabric B, in which shallow tier homogenisation was followed by low intermediate to deep tier (*Zoophycos* + *Chondrites* +/- ?*Asterosoma*) reworking, suggesting suppression of intermediate tier forms due to restricted oxygen below the shallowest zone. It differs from ichnofabric B only in the density of *Zoophycos* traces, possibly due to a slight decrease in sedimentation rates. In interpretation of the equivalent fabric (Ichnofabric 4), Damholt (2003) suggested that this fabric recorded the transition from normal to anoxic/dysoxic conditions.

Ichnofabric D

This fabric displays the most diverse trace fossil assemblage. Superimposed on the background mottling formed in the shallow tier are intermediate tier forms – *Planolites, Palaeophycus, Teichichnus, Taenidium, Thalassinoides* – and lower intermediate to deep tier forms – *?Asterosoma, Zoophycos, Chondrites*. A number of these forms occur only sporadically (*Teichichnus, Taenidium, Thalassinoides*) but the overall fabric testifies to a well-oxygenated sediment column under "normal" sedimentation rates, such that the sediment passed through a well-differentiated expanded tier profile, approximating to the idealised profile Fig. 7). The scarcity of *Thalassinoides* overall reflects the deeper water character of the Central Graben chalks (cf. Ekdale & Bromley 1984).

At certain levels, representatives of this ichnofabric show a dominance of one or another of the intermediate tier traces. A distinctive example of this is the local dominance of ?Asterosoma (e.g. Appendix 2, 6931–6929 ft). The implications of such local features are not considered further here, especially given the uncertain taxonomic position of this trace.

Ichnofabric E

This fabric is recognised only at the top of the Tor Formation, at the level of the distinctive hardground capping the formation, and tentatively in the two thin incipient hardgrounds lower in the formation in M-10X (Fig. 2). A description of these occurrences is given under lithofacies 4. At the top Tor Formation hardground, a complex, cross-cutting *Thalassinoides* fabric is developed through 2–4 ft of sediment; the contrasting lithologies and biostratigraphic ages of the fills of the *Thalassinoides* galleries reflects a complex and protracted evolution during which open burrow systems were filled /flushed under a period of slow or non-sedimentation. Borings both on the hardground surface and at the irregular margins of the *Thalassinoides* galleries testify to the cemented nature of the uppermost sediment layer. The stratigraphic signature of this horizon is discussed elsewhere (Ineson *et al.* 2004a); the development of this intense *Thalassinoides* fabric reflects slowing and cessation of sedimentation under well oxygenated and probably energetic, relatively shallow conditions such that the high intermediate tier fabric is preserved in a "frozen profile".

Depositional setting/stratigraphic evolution

The aim of this integrated project was to combine isotope, palynofacies and palaeoecological data, tightly constrained within a refined biostratigraphic framework, in order to better understand the depositional and palaeoceanographic evolution of the Late Maastrichtian in the Central Graben region. Sedimentological observations can contribute to this understanding but full discussion of the Late Maastrichtian palaeoenvironmental evolution is reserved for the integrated analysis (Ineson *et al.* 2004b). This summary is limited to the overall sedimentological observations from the M-10X and E-5X cored sections.

In general, the sedimentology documented here (basic documentation provided by the detailed core logs, Appendices 1, 2) confirms the well-known depositional scenario for the Maastrichtian of the southern Danish Central Graben (Surlyk *et al.* 2003). Deposition of chalk ooze was primarily a passive, low energy process involving pelagic settling in association with small-volume, low density turbidity currents and suspension clouds depositing mm-thick flow events (Damholt 2003; Damholt & Surlyk, in press). Minor sediment instability is indicated locally (in the upper levels of the E-5X section on the Tyra–Igor inversion ridge; Fig. 1) by the presence of small rooted slump folds but significant redeposition in the form of mass flow deposits (debrites, thick slide/slump sheets etc.) is not identified and indeed is atypical of the southern part of the Danish Central Graben in general (Surlyk *et al.* 2003). Bottom conditions varied from poorly oxygenated (anoxic/dysoxic) to well ventilated and, as discussed below, this variation is demonstrable both stratigraphically and spatially.

M-10X

This well was drilled on the western flank of the Dan Field, which is thought to have formed a weak structural high in Maastrichtian times, atop a salt dome (see discussion in Scholle *et al.* 1998). The cored Upper Maastrichtian section spans the *I. cooksoniae – P. grallator* dinoflagellate Zones (Fig. 2); the section is 219 ft thick, of which 73% is presently available as coherent slabbed core. The section is dominated by bioturbated chalk mudstones (lithofacies 3, 61%) and laminated chalk mudstones (lithofacies 1 and 2, 32%). Detailed sedimentological observations are given on the core logs (Appendix 1); three major aspects of the M-10X succession are covered here.

The succession is readily subdivided into two major units, described separately below.

6658 ft – 6530 ft 3 in.: Cyclic laminated–bioturbated chalk

In this lower portion of the core, the characteristic feature is the alternation of laminated and bioturbated chalk mudstones (Fig. 8). Laminated fabrics (lithofacies 1, 2) form about half of this interval (49%), as indicated by Damholt & Surlyk (in press) for roughly this stratigraphic interval. The ichnofabrics reflect this laminated–bioturbated cyclicity (Fig. 9). Diverse, well-developed fabrics (ichnofabric D) are scarce (6%) and the interval is dominated by alternations of laminated weakly bioturbated chalks (ichnofabric A1; 32%) and burrowed but low diversity (deep tier) fabrics (ichnofabric B; 30%).

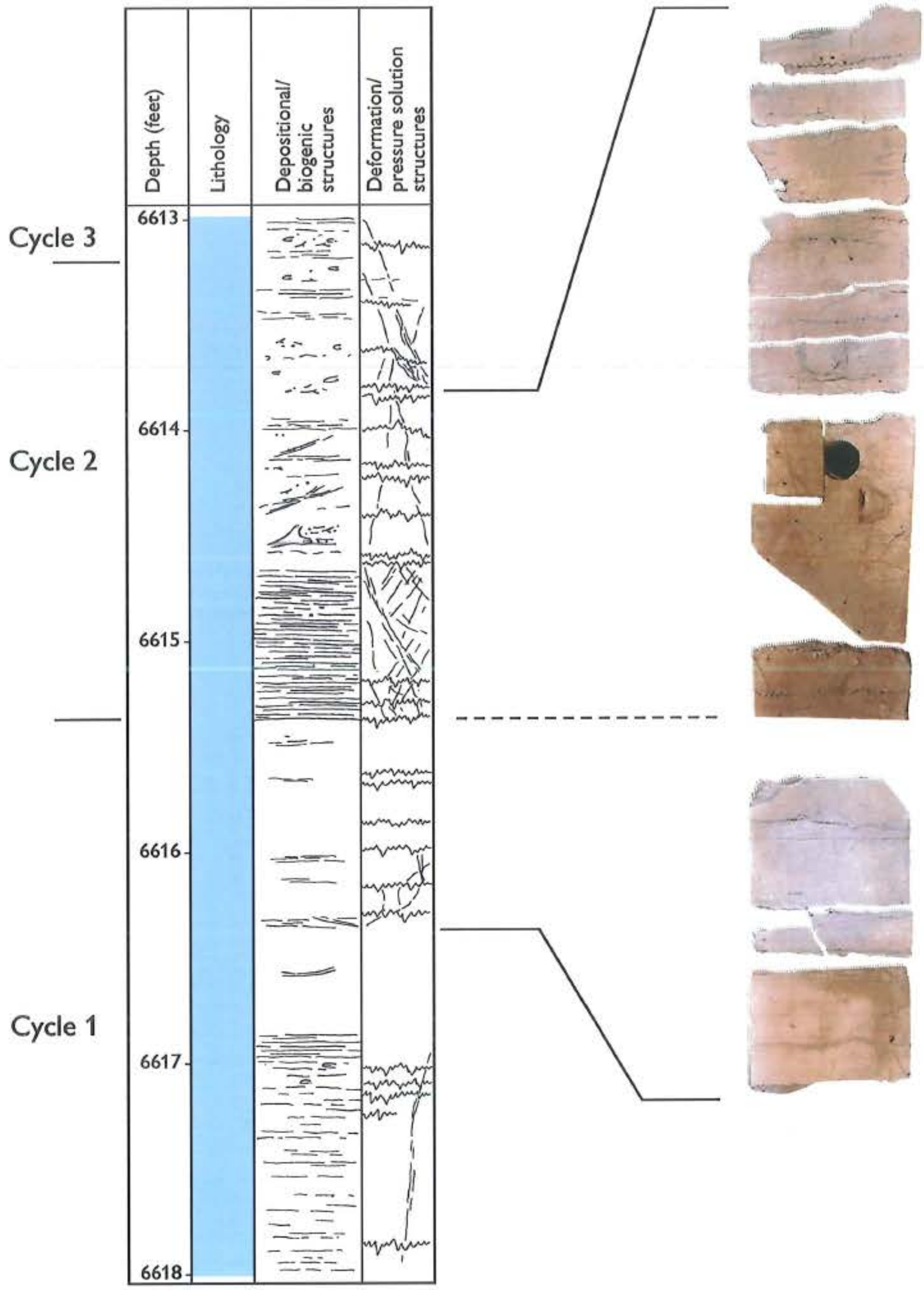


Fig. 8. Detailed log and core photograph showing the laminated–bioturbated cyclicity typical of the lower half of the Maastrichtian cored section in M-10X. The interval illustrated forms part of the section selected for detailed study of such cyclic sedimentation (see Fig. 2). Note the enhanced (brown) hydrocarbon staining in the more porous laminated half-cycles relative to the intervening bioturbated chalks.

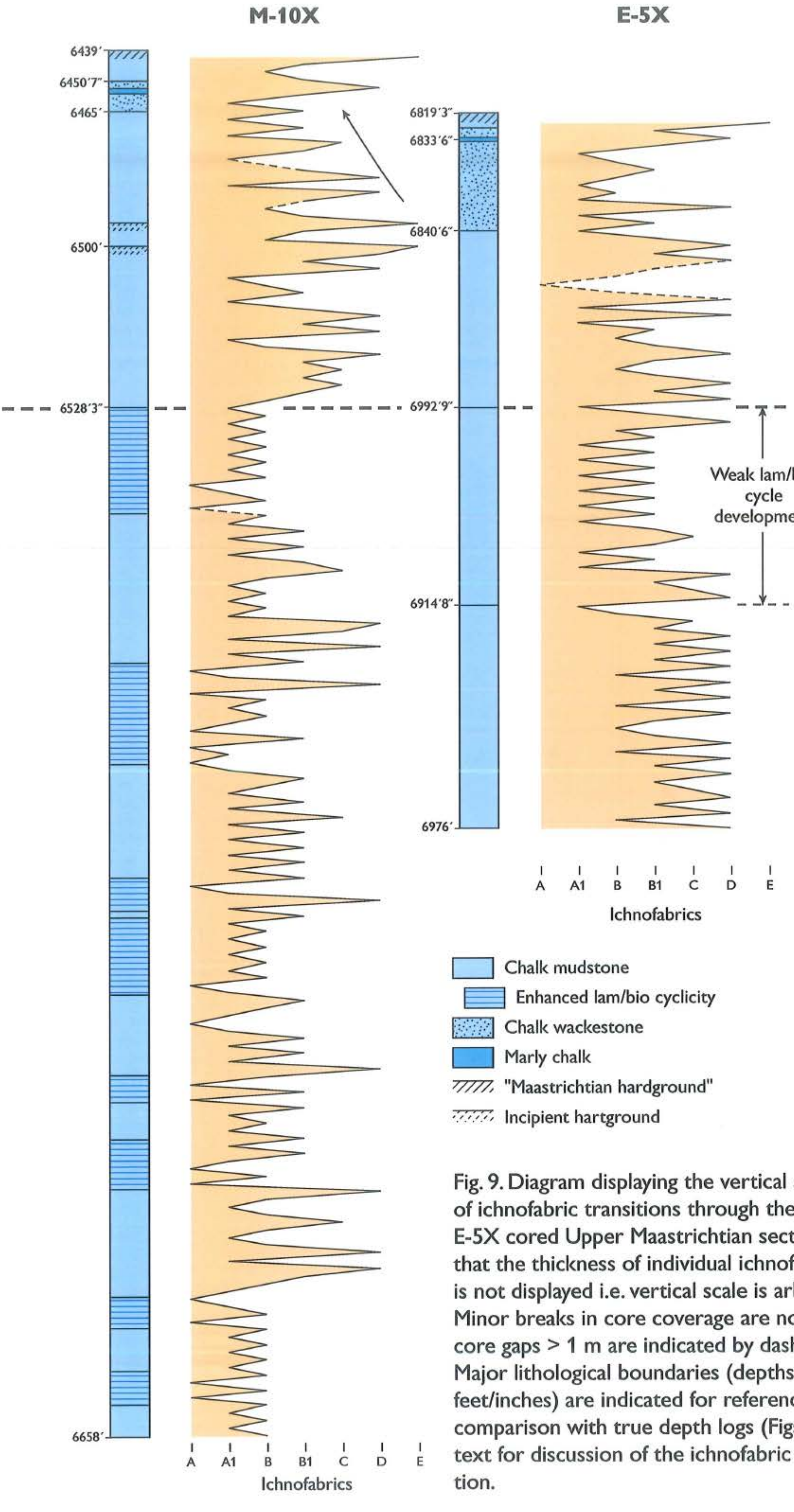


Fig. 9. Diagram displaying the vertical succession of ichnofabric transitions through the M-10X and E-5X cored Upper Maastrichtian sections. Note that the thickness of individual ichnofabric units is not displayed i.e. vertical scale is arbitrary. Minor breaks in core coverage are not indicated; core gaps > 1 m are indicated by dashed lines. Major lithological boundaries (depths in feet/inches) are indicated for reference and comparison with true depth logs (Figs 2, 3). See text for discussion of the ichnofabric distribution.

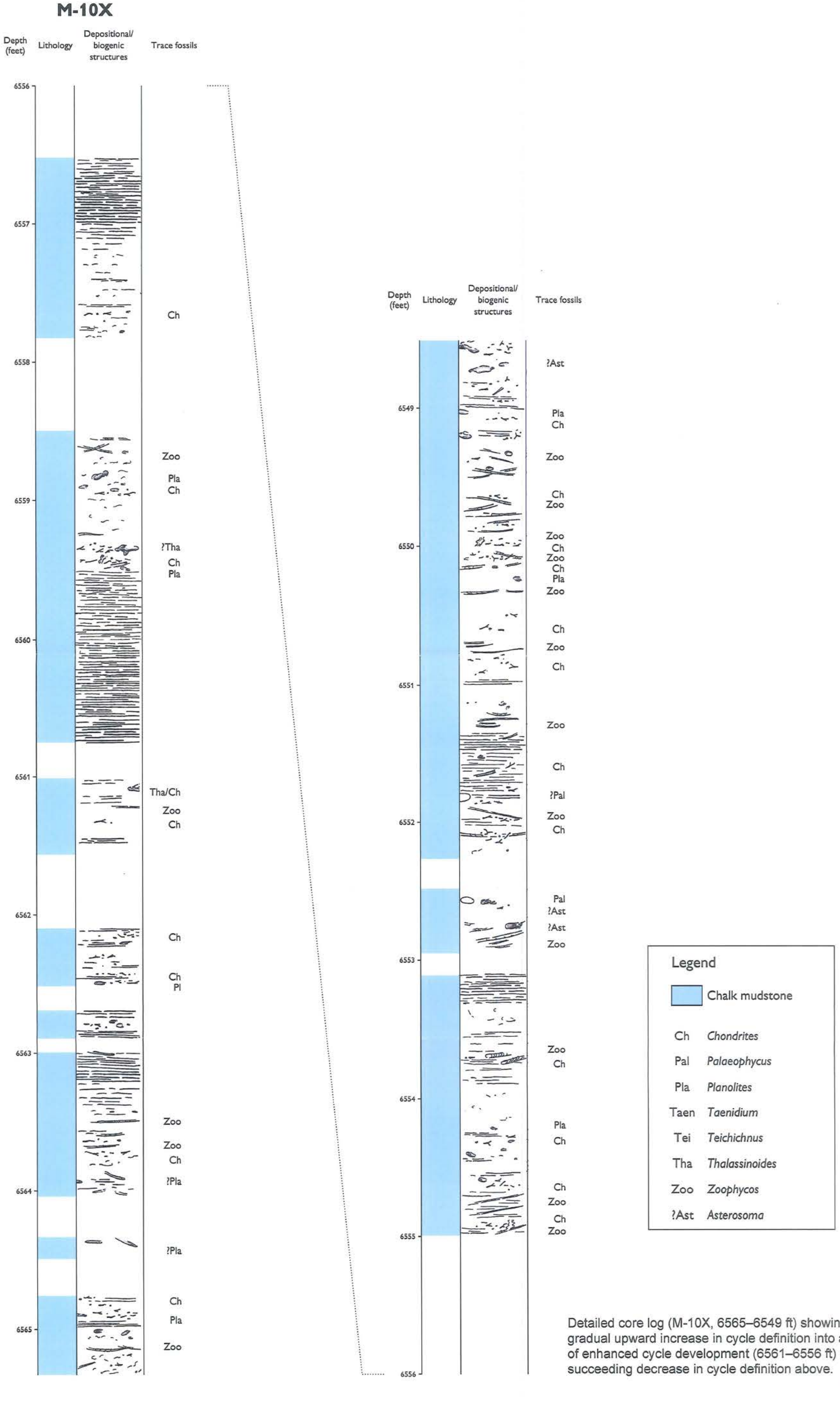
This cyclicity has been described and interpreted in detail by Damholt (2003) and Damholt & Surlyk (in press) and their process interpretations are followed here (see discussion above). It should be noted, however, that the degree or strength of cycle development is variable up-section. At certain levels (Fig. 2), a regular laminated–bioturbated cyclicity is well-developed with a cycle thickness of 2–4 ft, in broad agreement with the average of 1.25 m recorded by Damholt (2003). Where well-developed, the laminated half-cycle is typically about 1 ft thick, the corresponding bioturbated portion averaging 2–3 ft. At other levels, this cyclicity is poorly developed, either due to thinner alternations of bioturbated and laminated chalk or to a dominance of bioturbated chalk with rare thin laminated intervals (Fig. 2, Appendix 1). As shown in Fig. 2, the intervals showing enhanced cycle development alternate regularly with intervals of poor cycle development and in some cases a gradual upward increase in cycle definition is observed, culminating in a peak with well-developed cycles involving relatively thick well-laminated half-cycles, followed by an upward deterioration in cycle definition (Fig, 10). The intensity of cycle development thus appears to reflect a higher order of cyclicity superimposed on the short term cycles described by Scholle *et al.* (1998), Damholt (2003) and Damholt & Surlyk (in press). Since laminated chalk mudstones have been demonstrated to possess higher porosities than their intervening bioturbated counterparts (Toft *et al.* 1996; Scholle *et al.* 1998), it is not surprising that the higher order culminations in cycle definition (Figs 2, 10) correspond to major peaks on the petrophysical porosity log data – peaks that have formed the basis for reservoir cyclostratigraphy in the Upper Maastichtian chalks (Toft *et al.* 1996; Petersen *et al.* 2003).

In short, the sedimentological data from the M-10X well for this lower interval indicate a low energy environment, prone to the regular development of low oxygen conditions on the sea floor. Work by Stage (1999, 2001), Scholle *et al.* (1998), Damholt (2003) and Damholt & Surlyk (in press) indicates that the short-term m-scale laminated–bioturbated cycles may represent c. 22,000 year cycles in the Milankovitch frequency band and their distribution and degree of development suggests bundling into higher order cycles in the order of 30 ft (10 m) thick.

6528 ft 3 in. – 6438 ft.: Bioturbated chalk

The upper half of the cored section contrasts markedly with the lower with respest to the development of laminated–bioturbated cycles. Lamination is only locally developed between 6530 ft and the top of the Maastrichtian at 6439 ft and lithofacies 1 and 2 form only 6% of the preserved core in this interval. It is also notable that the laminated–bioturbated cyclicity ceases fairly abruptly at 6530 ft – there is no protracted gradational decrease in the degree of cycle development at this level (see Appendix 1). This shift is considered to record a significant environmental/oceanographic change in the evolution of the Danish Central Graben in the Late Maastrichtian and is discussed further in Ineson *et al.* (2004b).

Lithologically, the upper half of the M-10X cored section is overwhelmingly dominated by bioturbated chalk mudstones (nearly 80%) and as such lithofacies analysis provides little useful sedimentological information, beyond the location of rare, thin weakly laminated beds, incipient hardgrounds (see below), a distinctive thin marly unit and an associated facies change with increased skeletal debris in the uppermost Maastrichtian (Fig. 2; see below).Through the bulk of the section, however, greater resolution can be obtained from an analysis of the distribution of ichnofabrics. Concomitant with the marked decrease in the



Detailed core log (M-10X, 6565–6549 ft) showing the gradual upward increase in cycle definition into a zone of enhanced cycle development (6561–6556 ft) and the succeeding decrease in cycle definition above.

Fig. 10

occurrence of lamination (above 6528 ft 3 in.), the range of ichnofabrics present increases notably (Figs 9, 11), especially between the base of the unit (6528 ft 3 in.) and 6483 ft 10 in., spanning the interval including the incipient hardgounds (Fig. 2). In this interval, the more diverse fabrics (ichnofabrics C, D, E) are prominent (Fig. 9). Above 6483 ft 10 in., the burrowed chalk mudstone facies is dominated by ichnofabric B1 with the exception of a distinct ichnofabric D peak corresponding to the thin marly chalk interval at 6458 ft 3 in. – 6455 ft 6 in. (see below).

As described under lithofacies 4 (above), two closely spaced thin beds at 6499 ft 10 in. and 6497 ft 6 in. show a number of features symptomatic of hardened, firmground or incipient hardground layers. As such, they testify to periods of slow or non-sedimentation, probably due to winnowing by weak bottom currents. Given that these beds are associated with an interval showing evidence of increased infaunal diversity (see above), reflecting well-oxygenated surficial sediments, these hardened layers may record an increase in energy levels at the sea floor accompanying a relative sea-level change or a shift in circulation systems in this "deep shelf" setting. This subject is considered further in association with other datasets in Ineson *et al.* (2004b).

As noted above, a c. 2 ft thick weakly marly chalk interval, including discrete marlstone flasers, occurs towards the top of the Maastrichtian section (Fig. 2). This bed shows a diverse trace fossil assemblage (ichnofabric D) including *Thalassinoides* burrows, re-burrowed internally by *Chondrites*. In addition to the thin marly unit, the upper levels of the Maastrichtian section also illustrate a minor facies change (Fig. 2), particularly evident between 6465 ft 6 in. and 6450 ft 7 in., with the appearance of an increased proportion of fine skeletal detritus (for lithological description see lithofacies 5). The Upper Maastrichtian in M-10X is capped by a 4–5 ft mature hardground profile (see description and interpretation under lithofacies 4, above).

E-5X

This well, within the Tyra SE Field, is positioned on the Tyra–Igor ridge (Fig. 1), an important Late Cretaceous inversion structure (Fig.1). In terms of structural position, therefore, this well records the evolution of a structurally more positive region than the M-10X well. The cored Upper Maastrichtian section does not extend stratigraphically as deep as that in M-10X well; the base is within the *P. denticulatum* dinoflagellate Zone (Fig. 3), i.e. the lower *c.* 50 ft of the M-10X section is not represented in the E-5X core. The section is 156 ft thick, of which 66% is presently available as coherent slabbed core. The section is overwhelmingly dominated by bioturbated chalk mudstones (lithofacies 3, 82%) and, in contrast to M-10X, only about 6 % of the section comprises laminated chalk mudstones (lithofacies 1 and 2). Detailed sedimentological observations are given on the core logs (Appendix 2).

The bipartite division of the M-10X well into the lower laminated–bioturbated cyclic interval and the upper varied bioturbated interval (Fig. 2) is not evident in E-5 X. A weakly developed cyclic (laminated–bioturbated) unit is present, however, and provides a natural subdivision into three units.

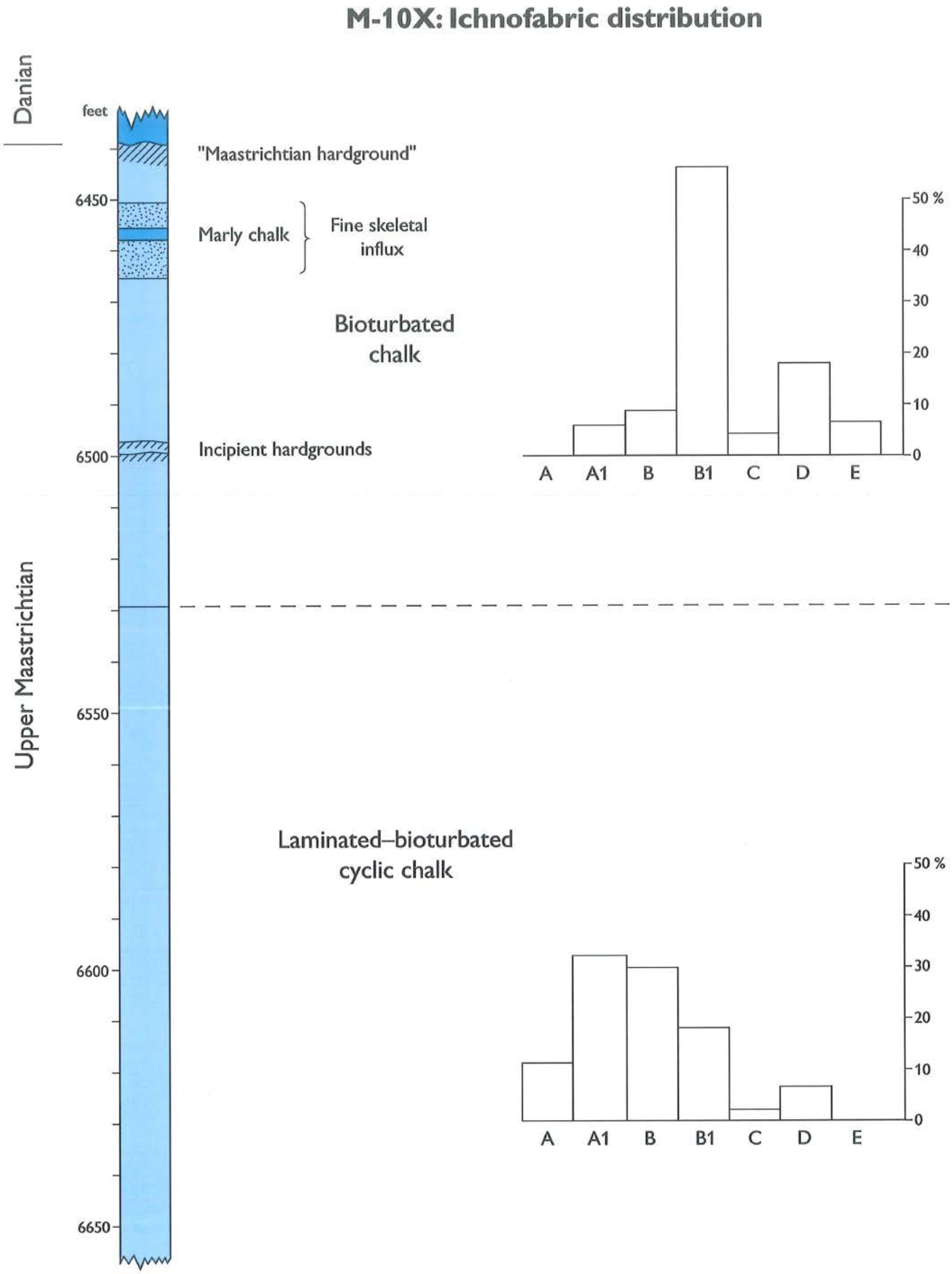


Fig. 11. Histograms of the relative proportions of the ichnofabrics A–D in the Upper Maastrichtian of the M-10X well, showing the marked shift in ichnofabric dominance from the lower laminated-bioturbated cyclic section to the upper predominately bioturbated and lithologically more varied part of the section (see also Fig. 9). For detailed biostratigraphic breakdown and legend, see Fig 2.

6975 ft 3 in. – 6915 ft: Lower bioturbated unit

This c. 60 ft unit corresponds broadly to the central portion of the cyclic laminated–bioturbated succession in M-10X (6550–6000 ft approx.). It consists almost entirely of bioturbated chalk mudstones (lithofacies 3, 99%) with rare thin bioturbated wackestones. In terms of sea-floor conditions, therefore, the cyclic development of poorly oxygenated bottom waters that developed in the Dan Field area at this time (Damholt 2003; Damholt & Surlyk, in press) was not recorded in the Tyra area, at least not to the same degree.

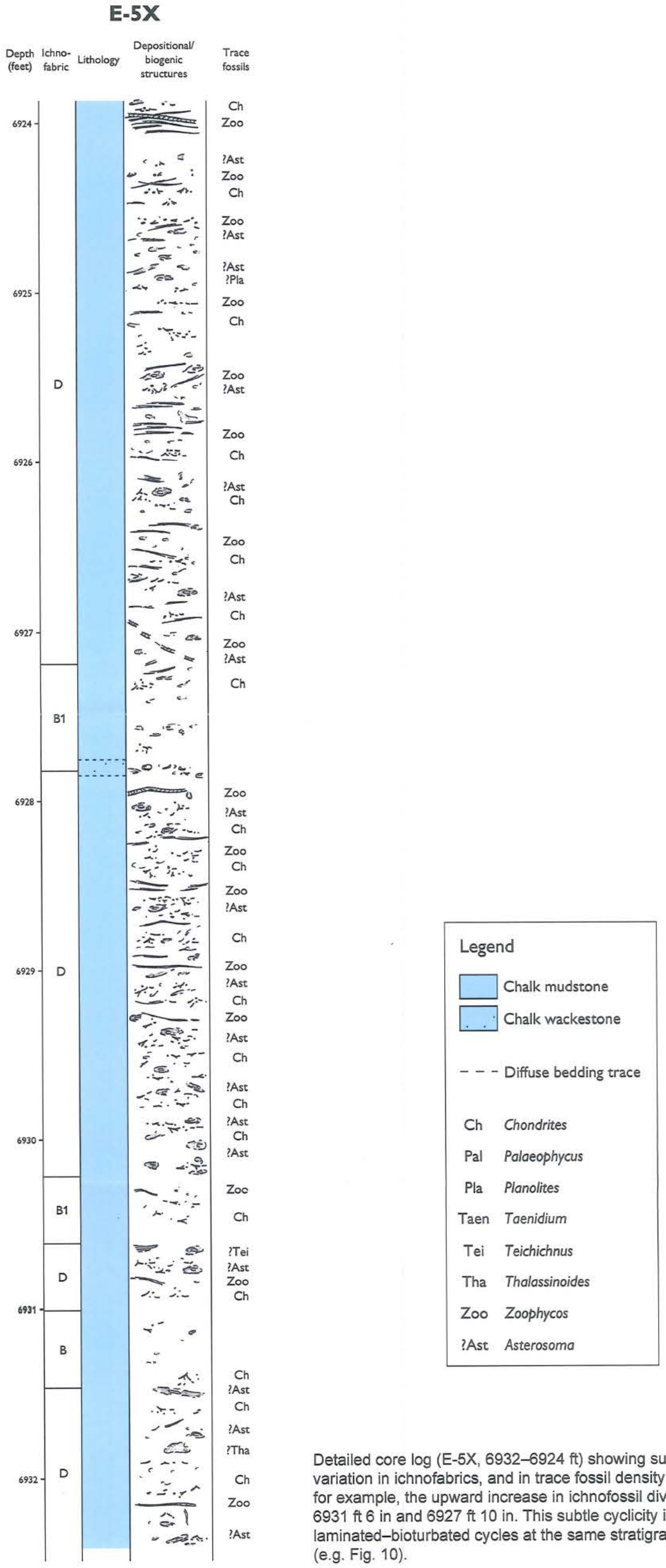
It is clear, however, from inspection of the detailed logs (Appendix 2) that although the laminated–bioturbated cyclicity is absent at this stratigraphic level in E-5X, a weak cyclicity can be recognised on the basis of the trace fossil distribution in the bioturbated chalk. For example, in the interval 6969–6954 ft (Appendix 2), gradational shifts are evident between ichnofabrics (B1–C–D) and within ichnofabrics, particularly ichnofabric D, where variations are seen in the density of trace fossils (picked out particularly by *Zoophycos*). The vague rhythmicity created by this variation in trace fossil fabric is in the order of 2–4 ft thick. Similarly, higher in the succession, cycles of this order of magnitude are recognisable on the basis of the alternation of ichnofabrics B and D (Fig. 12).

It can be concluded, therefore, that although the cyclic oxygen-deficient conditions inferred for the Dan Field area were not experienced so severely in the Tyra Field area, the variation in trace fossil fabrics, at roughly the same scale as the laminated–bioturbated cycles in M-10X, records contemporaneous shifts in oxygenation of bottom waters. Conditions were never so extreme as to exclude shallow burrowers and deep tier tolerant organisms, but controlled the presence/density of intermediate tier organisms. Thus, the premise that laminated–bioturbated cycles are the primary control on Upper Maastrichtian chalk porosity variation regionally in the Danish Central Graben, may be invalid, at least at certain stratigraphic levels. That said, and assuming that porosity variation in bioturbated sections is related to the nature of the biogenic fabric (Damholt 2003), then the correlation potential of log-defined porosity cycles (Toft *et al.* 1996) remains high, since the factors controlling the fluctuations in bottom water oxygenation were probably global in nature (Damholt & Surlyk, in press).

The geographic variation in the development of these short-term chalk cycles, from laminated–bioturbated to bioturbated–bioturbated, was probably controlled by an irregular seafloor topography in the Danish Central Graben – the Dan Field area lying in a topographically lower area than the Tyra Field on the Tyra–Igor inversion ridge.

6915–6892 ft 8 in.: weakly cyclic (laminated–bioturbated) unit

This short interval shows a weak laminated–bioturbated cyclicity, as developed in the M-10X section. The equivalent level in M-10X (6528–6520 ft, see Figs 2, 3) comprises an altenation of laminated or laminated/bioturbated chalks (ichnofabrics A, A1; 30%) with bioturbated chalks of ichnofabrics B/B1 (62%). In E-5X, weakly laminated/bioturbated chalks (ichnofabric A1; 26%) alternate with burrowed chalks showing a range of ichnofabrics (B/B1, 51%; C, 6%; D, 16%, see Fig. 9 and Appendix 2). Laminated units are typically up to a foot thick, locally to 2 ft, and alternate with burrowed intervals from 6 in. to 5 ft thick. Lamination is often diffuse, discontinuous and interrupted by discrete burrows or burrowed



Detailed core log (E-5X, 6932–6924 ft) showing subtle cyclicity defined by variation in ichnofabrics, and in trace fossil density within ichnofabrics – note, for example, the upward increase in ichnofossil diversity and density between 6931 ft 6 in and 6927 ft 10 in. This subtle cyclicity is at roughly the same scale as laminated–bioturbated cycles at the same stratigraphic level in the M-10X well (e.g. Fig. 10).

Fig. 12

patches. Laminated–bioturbated couplets range from 1 ft to 6 ft thick but are typically 2–3 ft thick, the same order of thickness as those in M-10X.

This interval clearly records an alternation of oxic and dysoxic conditions comparable to, but less extreme than, those experienced in the Dan Field area. Given that lamination is not preserved in the underlying unit in E-5X, the suggestion is that this interval, correlatable with the uppermost enhanced cyclic interval in M-10X, records one of the more extreme periods with respect to oxygen deprivation on the sea floor since structurally more positive settings were also affected, albeit to a lesser degree.

6892 ft 8 in. – 6819 ft 3 in.: upper bioturbated unit

This upper sedimentary packet, corresponding to the largely non-cyclic upper half of the cored section in the M-10X well (see Figs 2, 3), is dominated by burrowed chalk mudstones of lithofacies 3 (71%); just 7% of the preserved core shows lamination. The upper *c.* 27 ft of the section is more varied lithologically showing a higher proportion of fine skeletal material and a marly chalk bed (see below). A complex mature hardground is developed at the top of the Maastrichtian section. The lower *c.* 17 ft (up to 6876 ft) is a homogeneous burrowed chalk mudstone succession dominated by ichnofabric B with thin units (1–2 ft thick) showing a more diverse and higher density fabric (D) recurring at *c.* 5–6 ft intervals. Between 6876 ft and 6859 ft 6 in., the preserved core shows a more varied character. Both thin laminated beds (lithofacies 1, 2; ichnofabrics A/A1) and bioturbated beds (lithofacies 3) showing a diverse ichnofabric (D) are represented. Unfortunately, core preservation breaks down at this level and upwards to 6849 ft so that continuous detailed logging was not possible. This is particularly regrettable since this interval (*c.* 6873 ft) correlates with the level at which the incipient hardgrounds were recorded in the M-10X section – the manifestation of these surfaces in E-5X has thus not been ascertained.

A 1 ft thick bed of slightly marly chalk was logged at 6833–6934 ft in E-5X, showing a well-defined and diverse trace fossil assemblage (ichnofabric D, see Appendix 2). This bed is thought to correlate with a comparable unit in M-10X. As in M-10X, a distinct interval was recorded in the uppermost levels of the Upper Maastrichtian succession in which fine skeletal material is notably more dominant (creating a dispersed wackestone fabric). In E-5X, this facies is noted between 6846 ft 5 in. and 6825 ft. Although largely bioturbated (B/B1), the wackestones locally show impersistent lamination, often defined by dispersed fine skeletal grains; bryozoan fragments were noted in places. As in M-10X, the marly chalk bed occurs in this skeletal-rich interval. It should be noted that ichnofabric identification was hampered in this interval by reduced oil staining above the gas/oil contact at 6533 ft.

Poor core preservation or missing sections precluded study of the top Maastrichtian hardground surface itself although the remaining core pieces indicate a comparable development to that observed in M-10X (see under lithofacies 4, above).

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Appendix 1: M-10X core logs

Legend

Lithology

- 🟦 Chalk
  - 🟦 Mudstone
  - ░ Wackestone
  - ▒ Packstone/grainstone
- 🟦 Marly chalk
- 🟩 Marlstone
- 🟫 Chert

Fractures etc.

〰	Stylolite
S	Slip/shear plane
HH	Healed hairline fracture
SA	Stylolite-associated fracture
C	Calcite-cemented fracture
O	Open fracture

Bed boundaries

———	Well-defined
– – –	Diffuse bedding trace

Other abbreviations

blk	black
cs	coarse
gnl	granule
gnst	grainstone
gy	grey
m	medium
mlst	marlstone
v cs	very coarse
wkst	wackestone

Plugs etc.

○	Horizontal plug
I	Isotope sample
B	Biostratigraphic sample
▯	Polished slab

Bioturbation

Intensity

A	Absent
L	Low
M	Medium
H	High

Trace fossils

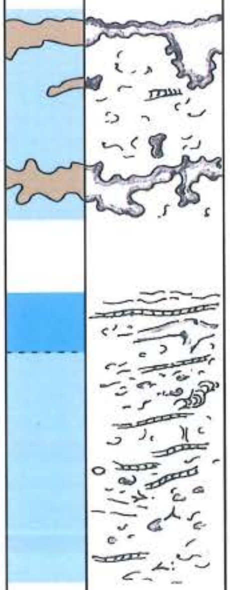
Ch	*Chondrites*
Hel	*Helminthopsis*
Pal	*Palaeophycus*
Pla	*Planolites*
Taen	*Taenidium*
Tei	*Teichichnus*
Tha	*Thalassinoides*
Zoo	*Zoophycos*
?Ast	*Asterosoma*

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Ekofisk Fm

Well : M-10X
Core : 4

Scale : c 1:10
Geologist / Logging date : Jl, 3/2002



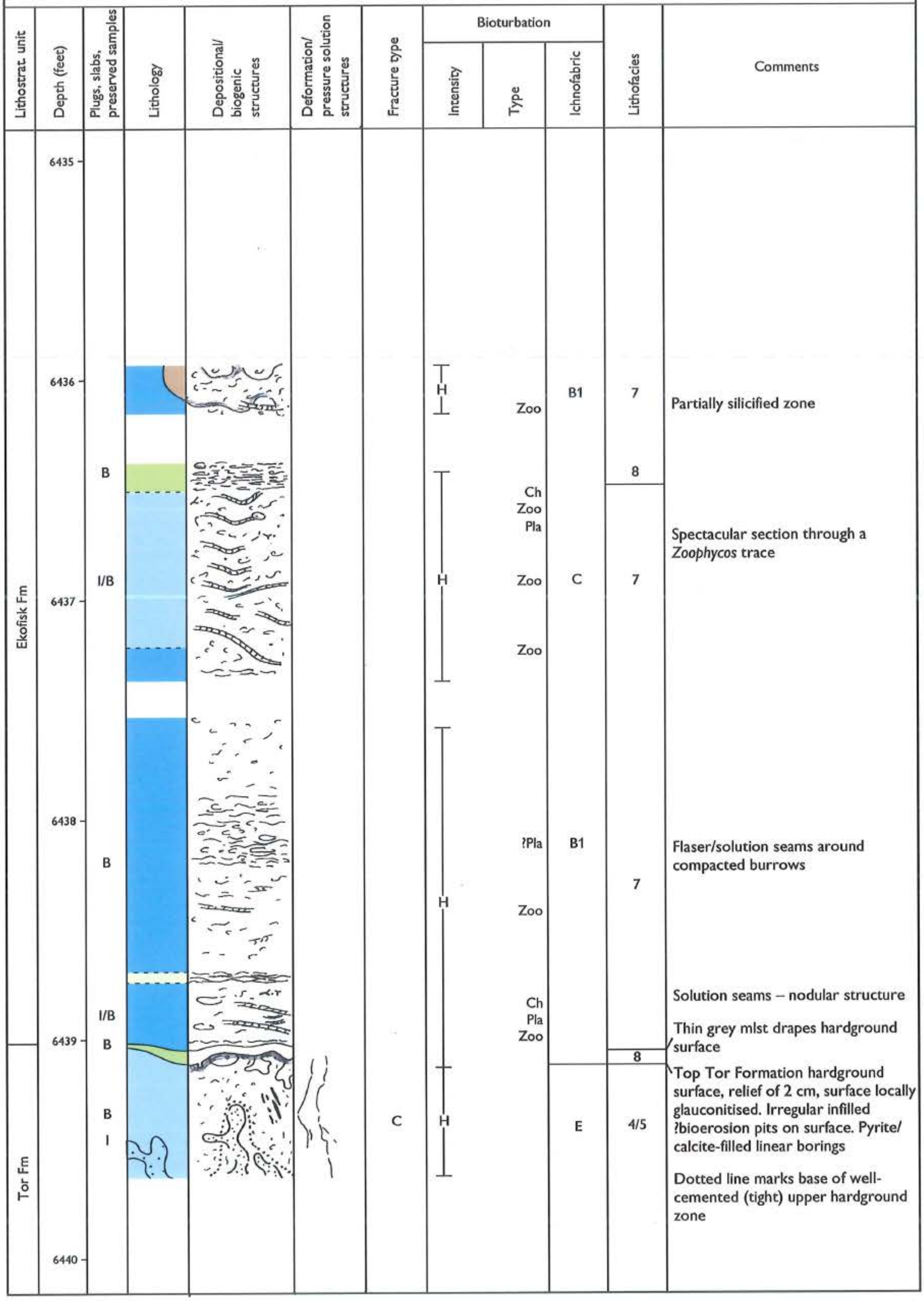
Lithostrat. unit	Depth (feet)	Plugs, slabs, preserved samples	Lithology	Depositional/ biogenic structures	Deformation/ pressure solution structures	Fracture type	Bioturbation			Lithofacies	Comments
							Intensity	Type	Ichnofabric		
Ekofisk Fm	6433						H	Zoo	B1	3	
		I/B									Strange mottled/nodular fabric – matrix chalk may be partly silicified
	6434						H	Zoo ?Tha		7	Solution seams
								?Taen			Back-filled burrow – irregular *Taenidium?*
								Zoo	D	3	Bivalve
		I/B									
		95 O						Zoo Ch Pla			
	6435										

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Ekofisk/Tor Fms

Well : M-10X
Core : 4

Scale : c 1:10
Geologist / Logging date : Jl, 3/2002



Partially silicified zone

Spectacular section through a *Zoophycos* trace

Flaser/solution seams around compacted burrows

Solution seams – nodular structure

Thin grey mlst drapes hardground surface

Top Tor Formation hardground surface, relief of 2 cm, surface locally glauconitised. Irregular infilled ?bioerosion pits on surface. Pyrite/ calcite-filled linear borings

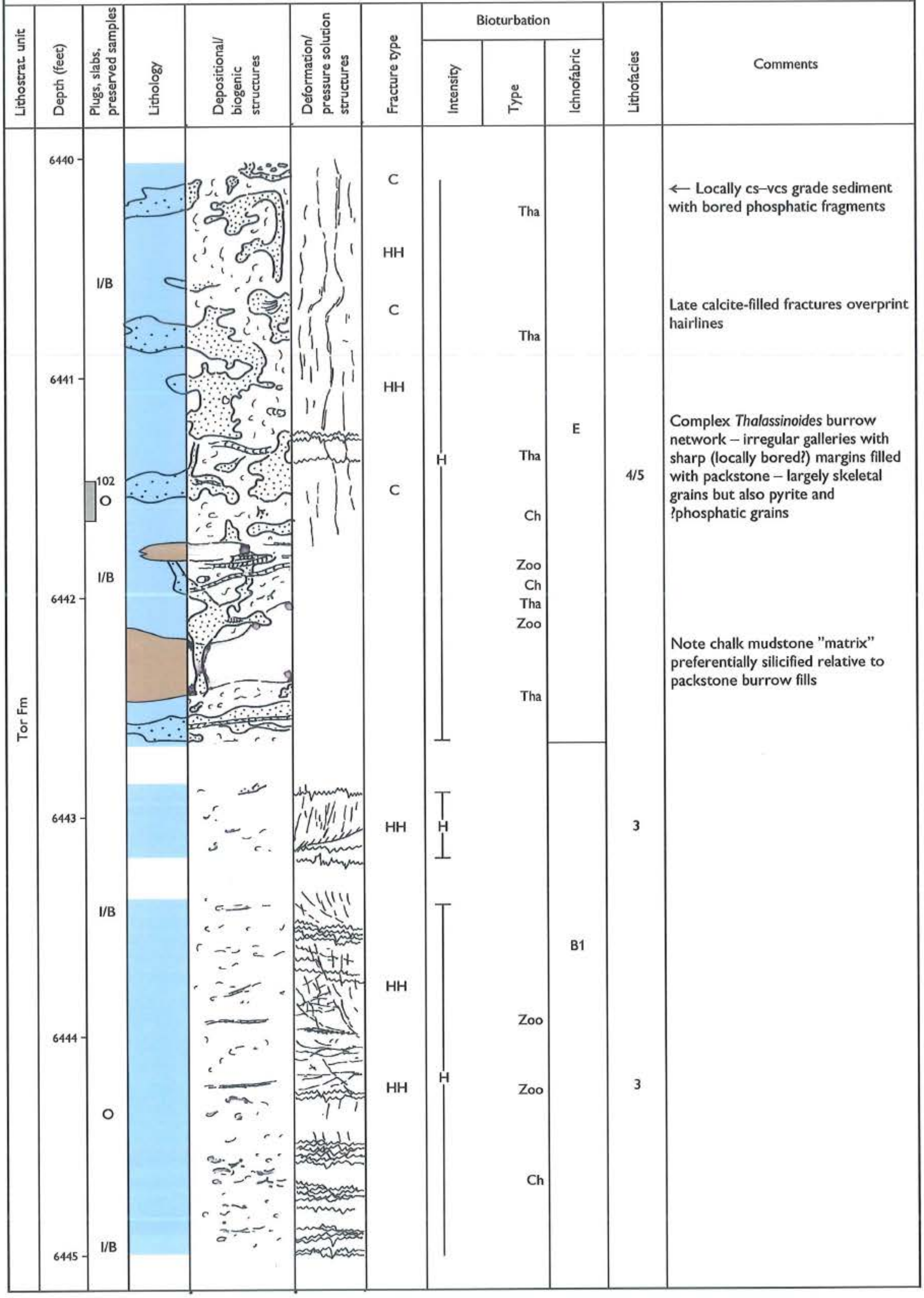
Dotted line marks base of well-cemented (tight) upper hardground zone

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 4

Scale : c 1:10
Geologist / Logging date : Jl, 3/2002



← Locally cs–vcs grade sediment with bored phosphatic fragments

Late calcite-filled fractures overprint hairlines

Complex *Thalassinoides* burrow network – irregular galleries with sharp (locally bored?) margins filled with packstone – largely skeletal grains but also pyrite and ?phosphatic grains

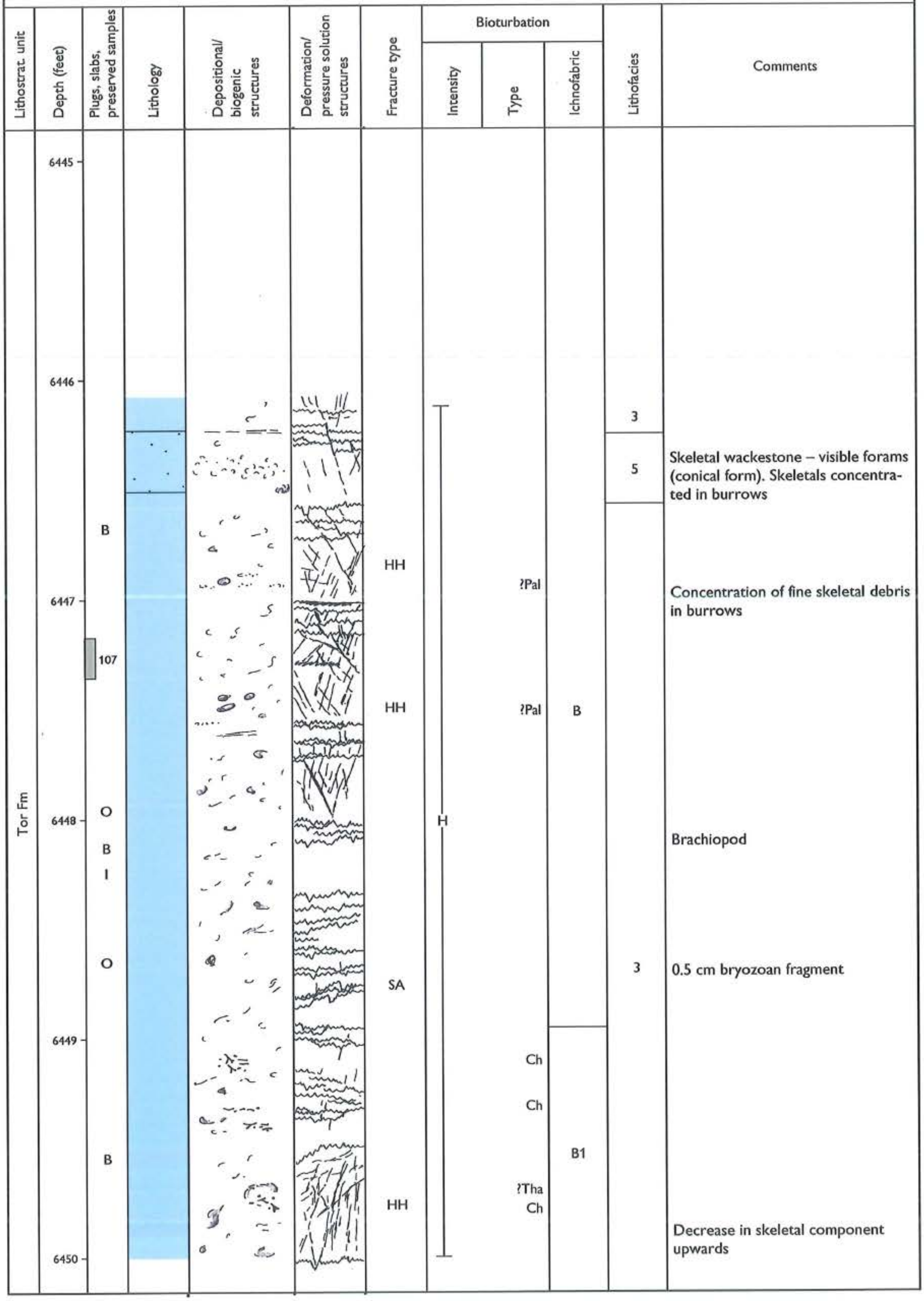
Note chalk mudstone "matrix" preferentially silicified relative to packstone burrow fills

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 4

Scale : c 1:10
Geologist / Logging date : Jl, 3/2002



Skeletal wackestone – visible forams (conical form). Skeletals concentrated in burrows

Concentration of fine skeletal debris in burrows

Brachiopod

0.5 cm bryozoan fragment

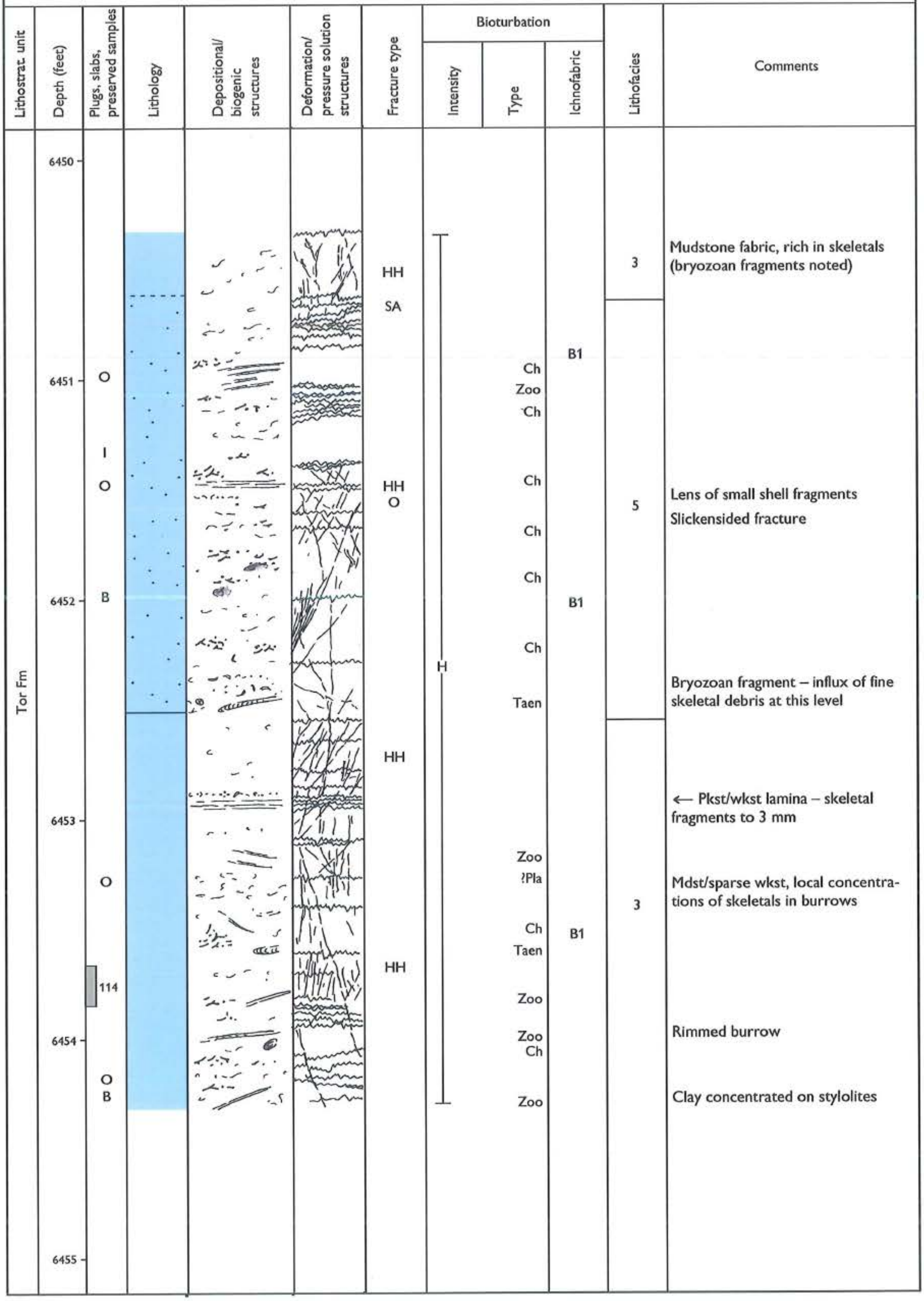
Decrease in skeletal component upwards

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 4

Scale : c 1:10
Geologist / Logging date : Jl, 3/2002



Mudstone fabric, rich in skeletals (bryozoan fragments noted)

Lens of small shell fragments
Slickensided fracture

Bryozoan fragment – influx of fine skeletal debris at this level

← Pkst/wkst lamina – skeletal fragments to 3 mm

Mdst/sparse wkst, local concentrations of skeletals in burrows

Rimmed burrow

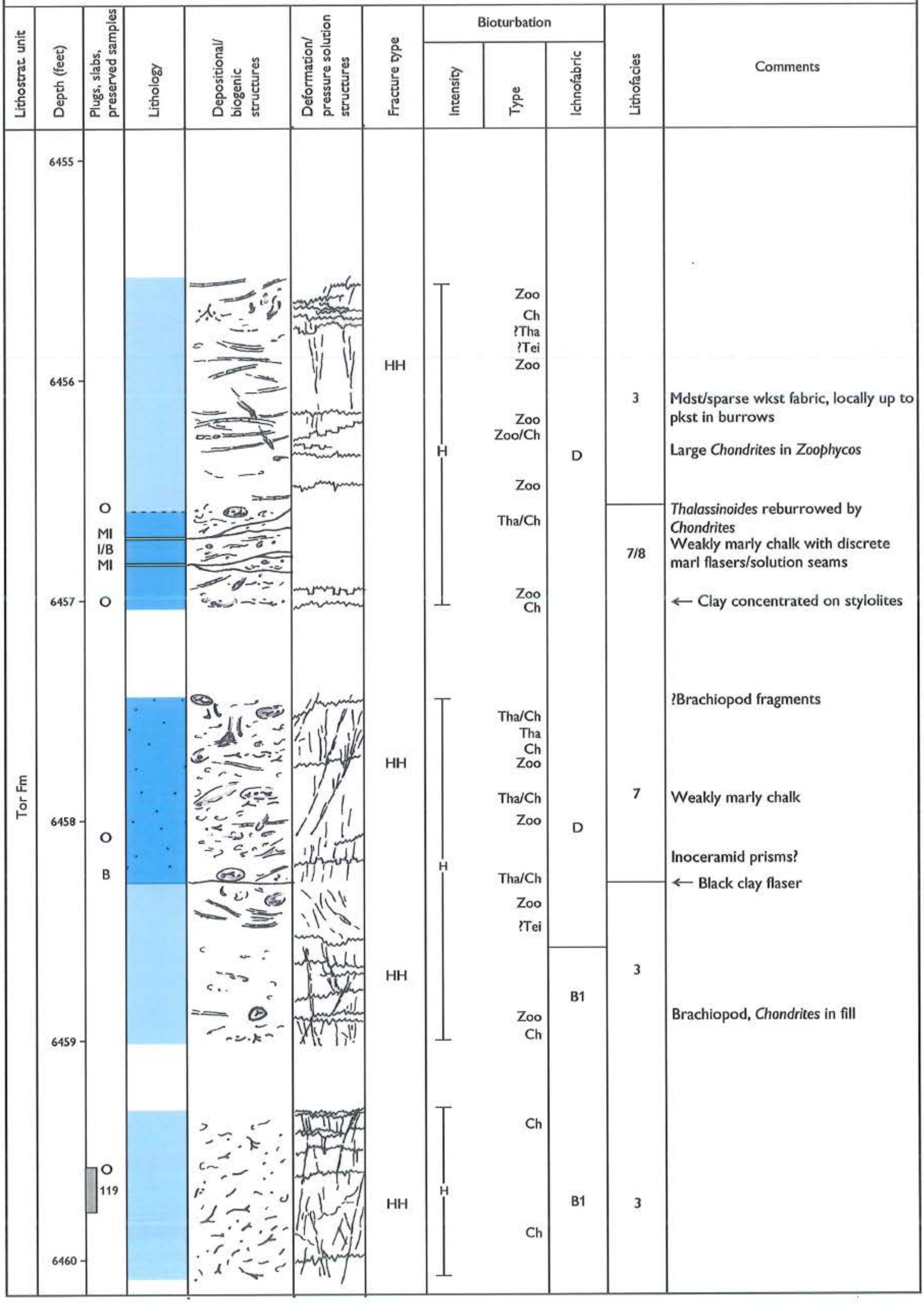
Clay concentrated on stylolites

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 4

Scale : c 1:10
Geologist / Logging date : Jl, 3/2002



Mdst/sparse wkst fabric, locally up to pkst in burrows

Large *Chondrites* in *Zoophycos*

Thalassinoides reburrowed by *Chondrites*

Weakly marly chalk with discrete marl flasers/solution seams

← Clay concentrated on stylolites

?Brachiopod fragments

Weakly marly chalk

Inoceramid prisms?

← Black clay flaser

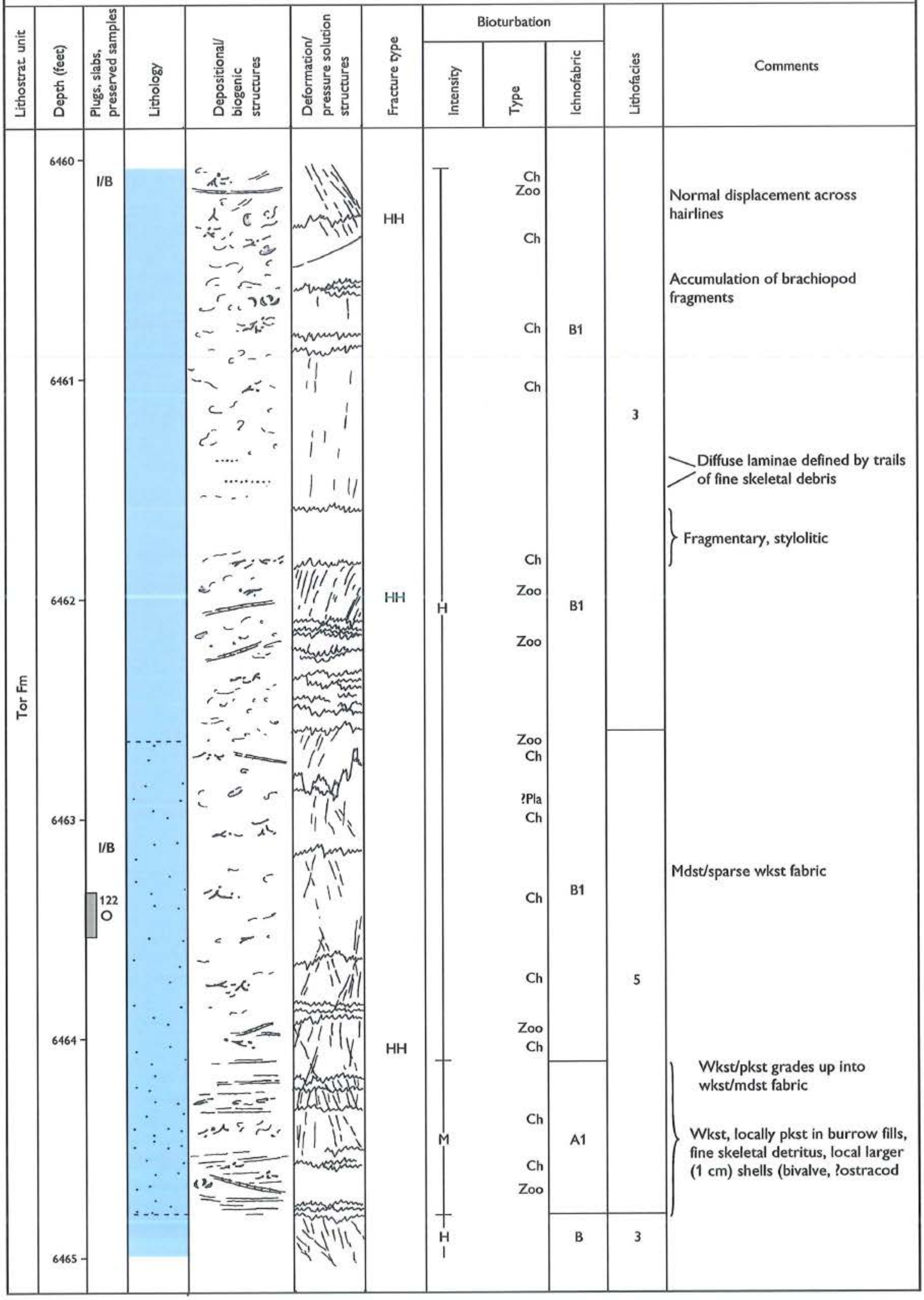
Brachiopod, *Chondrites* in fill

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 4

Scale : c 1:10
Geologist / Logging date : Jl, 3/2002



Normal displacement across hairlines

Accumulation of brachiopod fragments

Diffuse laminae defined by trails of fine skeletal debris

Fragmentary, stylolitic

Mdst/sparse wkst fabric

Wkst/pkst grades up into wkst/mdst fabric

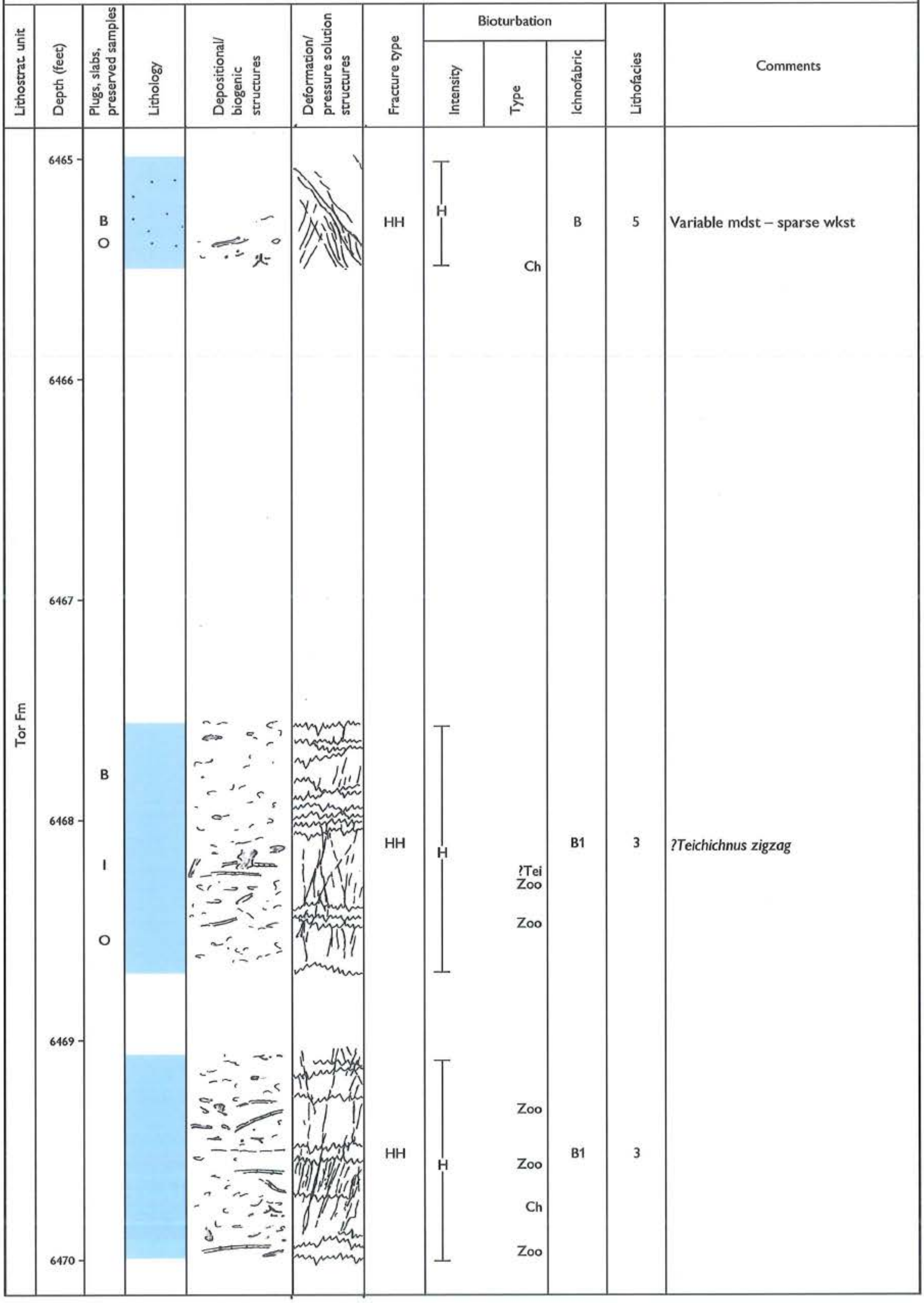
Wkst, locally pkst in burrow fills, fine skeletal detritus, local larger (1 cm) shells (bivalve, ?ostracod

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 4

Scale : c 1:10
Geologist / Logging date : Jl, 3/2002



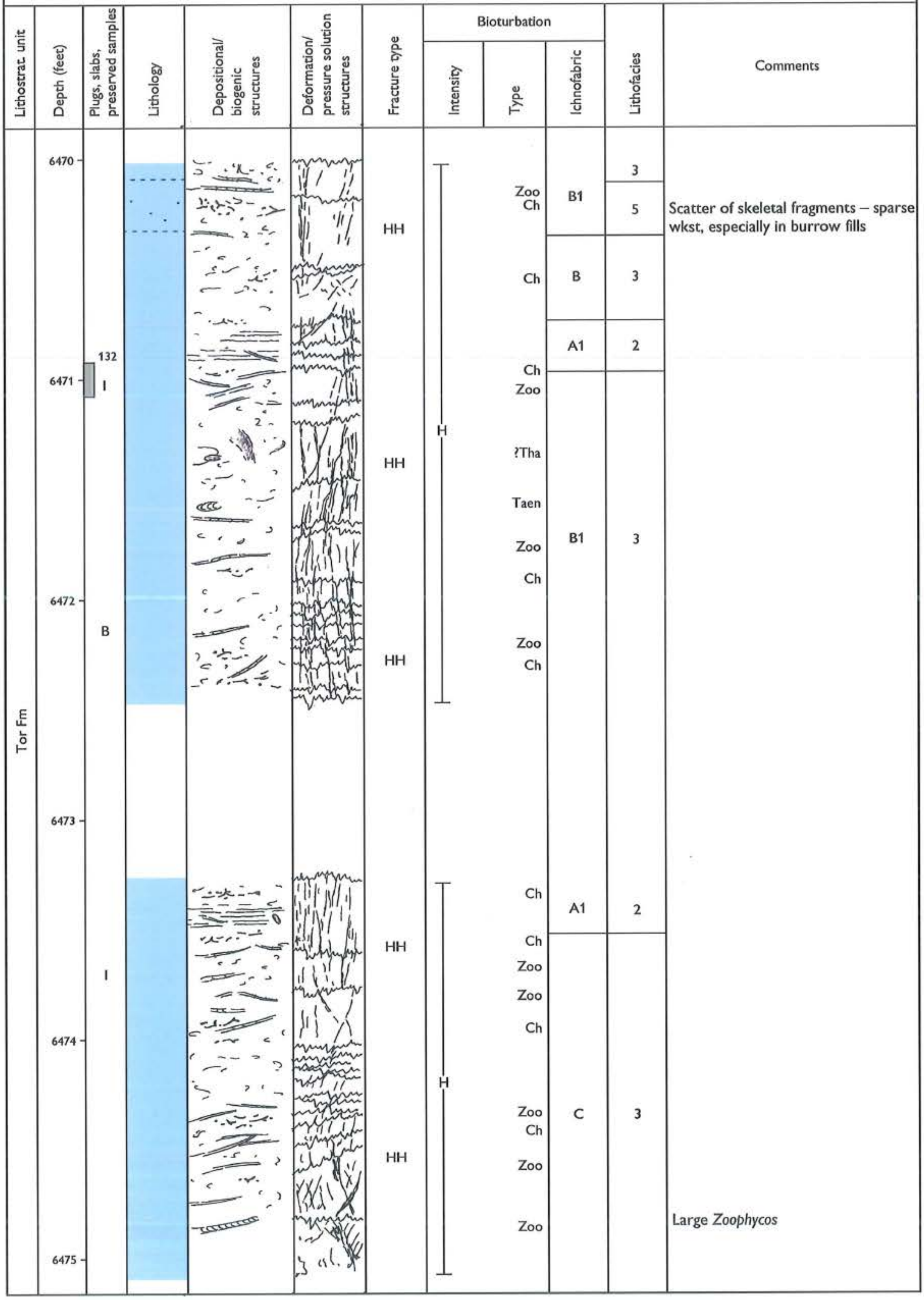
Lithostrat. unit	Depth (feet)	Plugs, slabs, preserved samples	Lithology	Depositional/ biogenic structures	Deformation/ pressure solution structures	Fracture type	Bioturbation Intensity	Bioturbation Type	Ichnofabric	Lithofacies	Comments
Tor Fm		B O				HH	H	Ch	B	5	Variable mdst – sparse wkst
		B I O				HH	H	?Tei Zoo Zoo	B1	3	*?Teichichnus zigzag*
						HH	H	Zoo Zoo Ch Zoo	B1	3	

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 4

Scale : c 1:10
Geologist / Logging date : Jl, 3/2002



Scatter of skeletal fragments – sparse wkst, especially in burrow fills

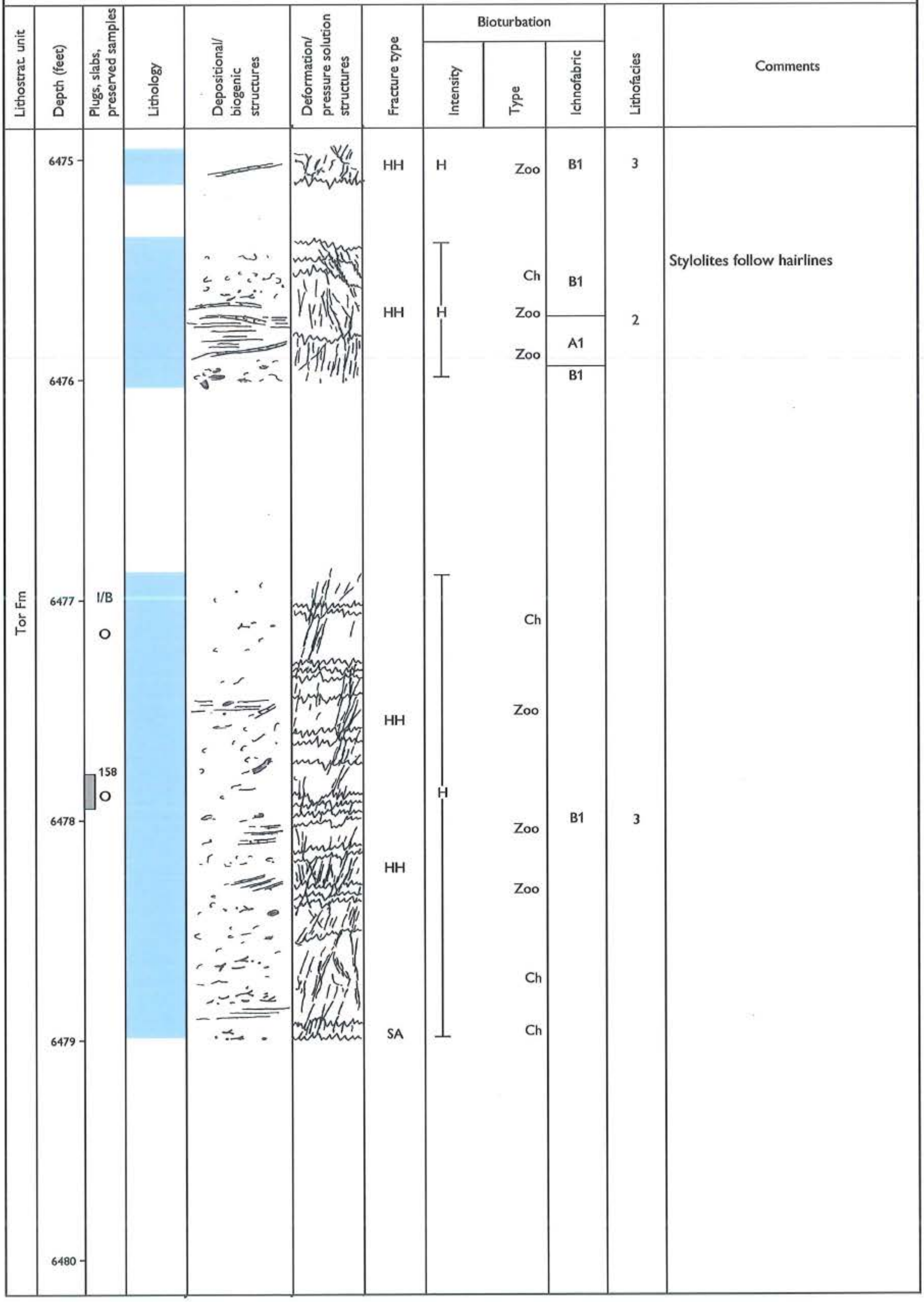
Large *Zoophycos*

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 4

Scale : c 1:10
Geologist / Logging date : Jl, 3/2002

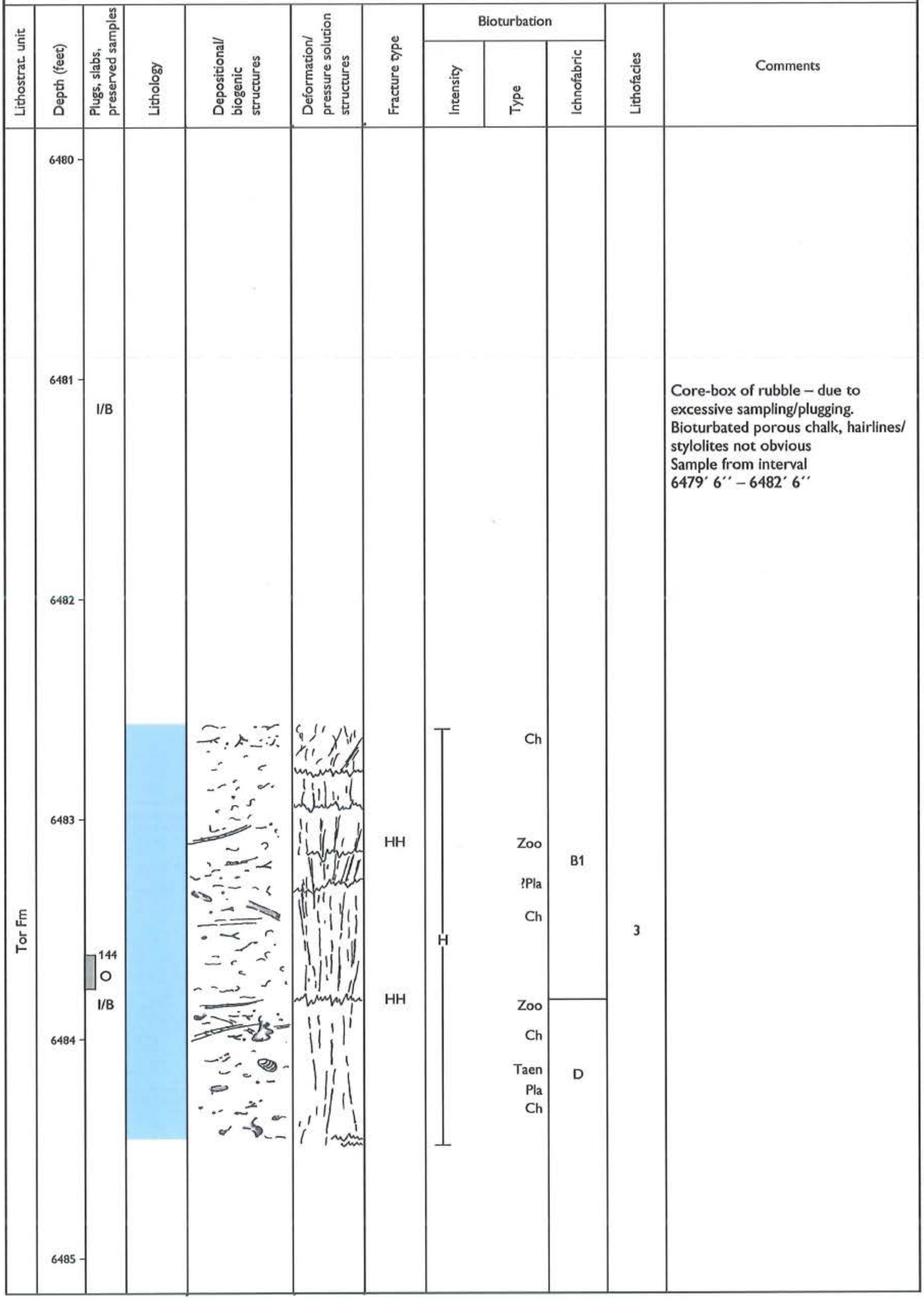


CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 4

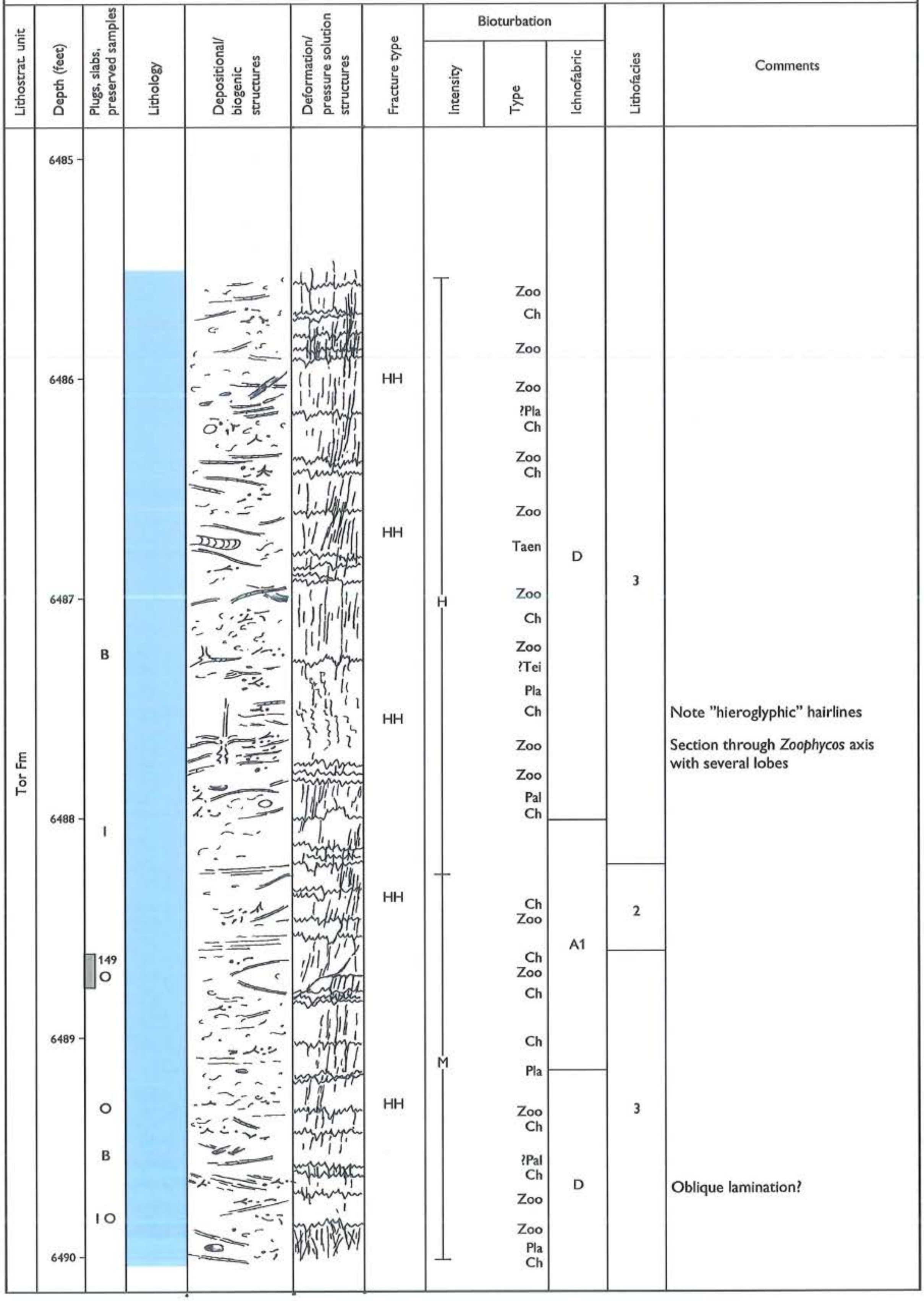
Scale : c 1:10
Geologist / Logging date : Jl, 3/2002



Core-box of rubble – due to excessive sampling/plugging.
Bioturbated porous chalk, hairlines/ stylolites not obvious
Sample from interval
6479′ 6′′ – 6482′ 6′′

CORE DESCRIPTION

Field / Area : Dan
Well : M-10X
Scale : c 1:10
Lithostrat. unit : Tor Fm
Core : 4
Geologist / Logging date : JI, 3/2002



Note "hieroglyphic" hairlines

Section through *Zoophycos* axis with several lobes

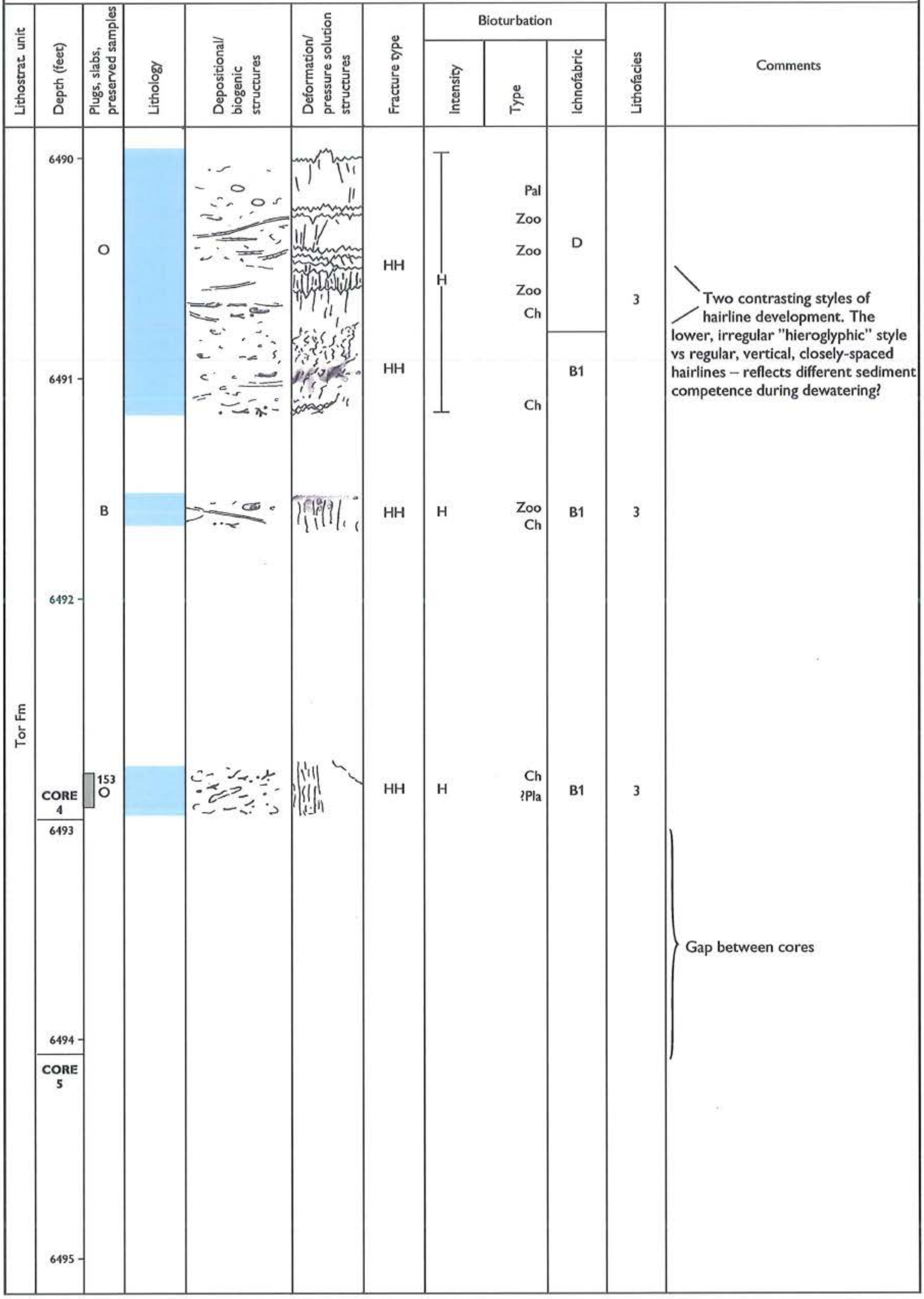
Oblique lamination?

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 4/5

Scale : c 1:10
Geologist / Logging date : Jl, 3/2002



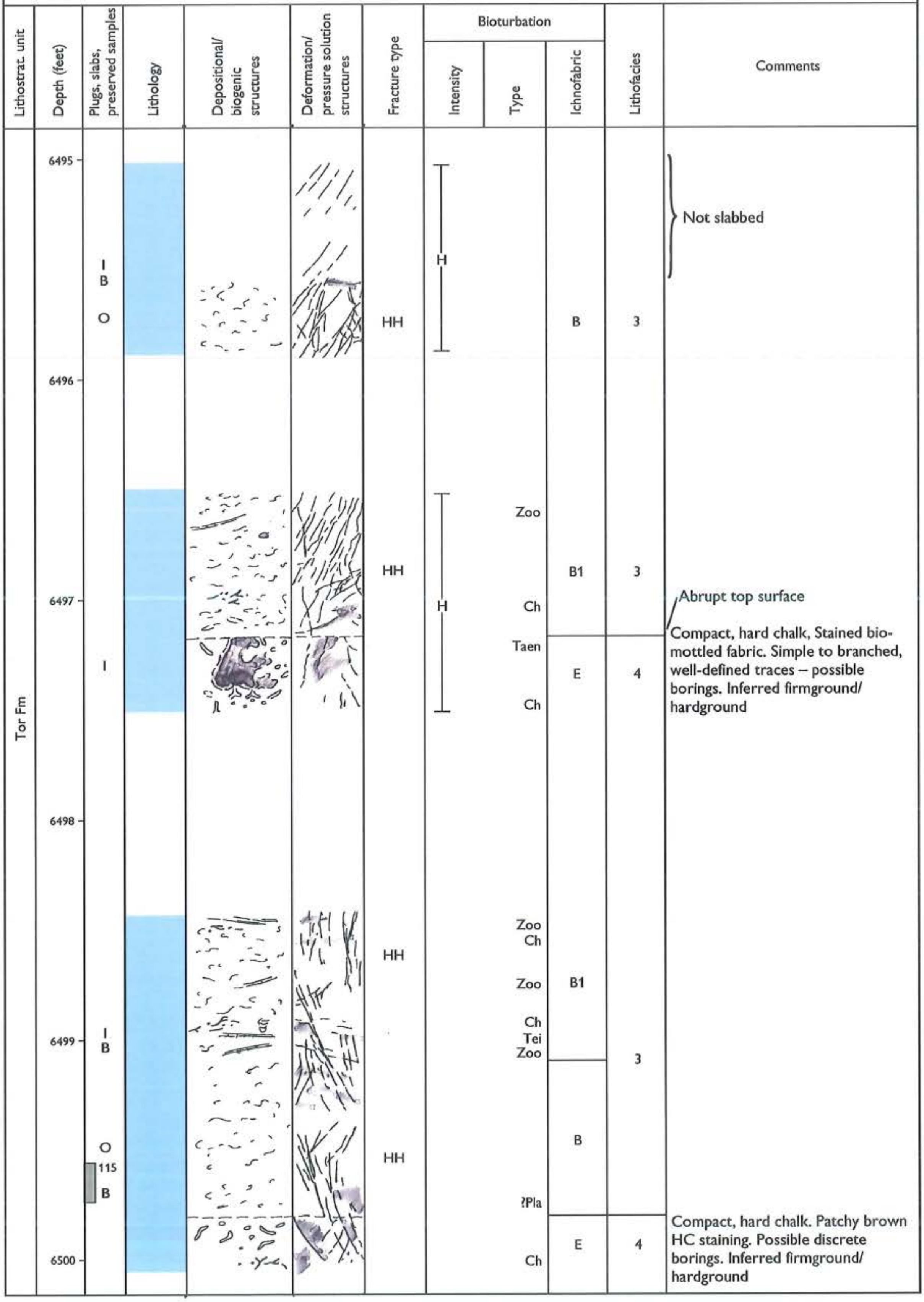
Lithostrat. unit	Depth (feet)	Plugs, slabs, preserved samples	Lithology	Depositional/ biogenic structures	Deformation/ pressure solution structures	Fracture type	Bioturbation Intensity	Bioturbation Type	Ichnofabric	Lithofacies	Comments
Tor Fm	6490	O				HH	H	Pal Zoo Zoo Zoo Ch	D	3	Two contrasting styles of hairline development. The lower, irregular "hieroglyphic" style vs regular, vertical, closely-spaced hairlines – reflects different sediment competence during dewatering?
	6491					HH		Ch	B1		
		B				HH	H	Zoo Ch	B1	3	
	6492	153 O				HH	H	Ch ?Pla	B1	3	
	CORE 4 6493										Gap between cores
	6494 CORE 5										
	6495										

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 5

Scale : c 1:10
Geologist / Logging date : Jl, 3/2002



Not slabbed

Abrupt top surface

Compact, hard chalk, Stained bio-mottled fabric. Simple to branched, well-defined traces – possible borings. Inferred firmground/ hardground

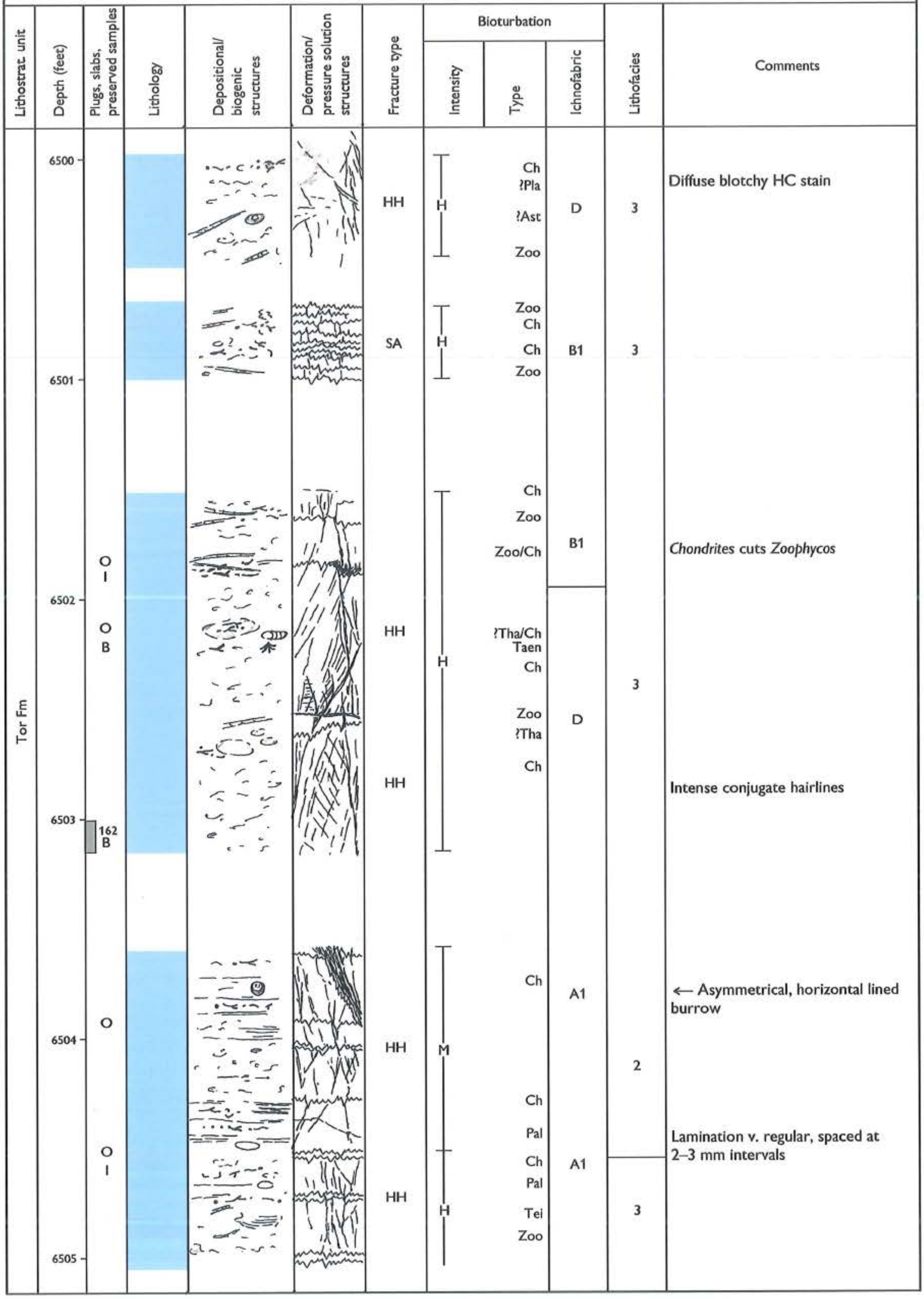
Compact, hard chalk. Patchy brown HC staining. Possible discrete borings. Inferred firmground/ hardground

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 5

Scale : c 1:10
Geologist / Logging date : Jl, 3/2002



Diffuse blotchy HC stain

Chondrites cuts *Zoophycos*

Intense conjugate hairlines

← Asymmetrical, horizontal lined burrow

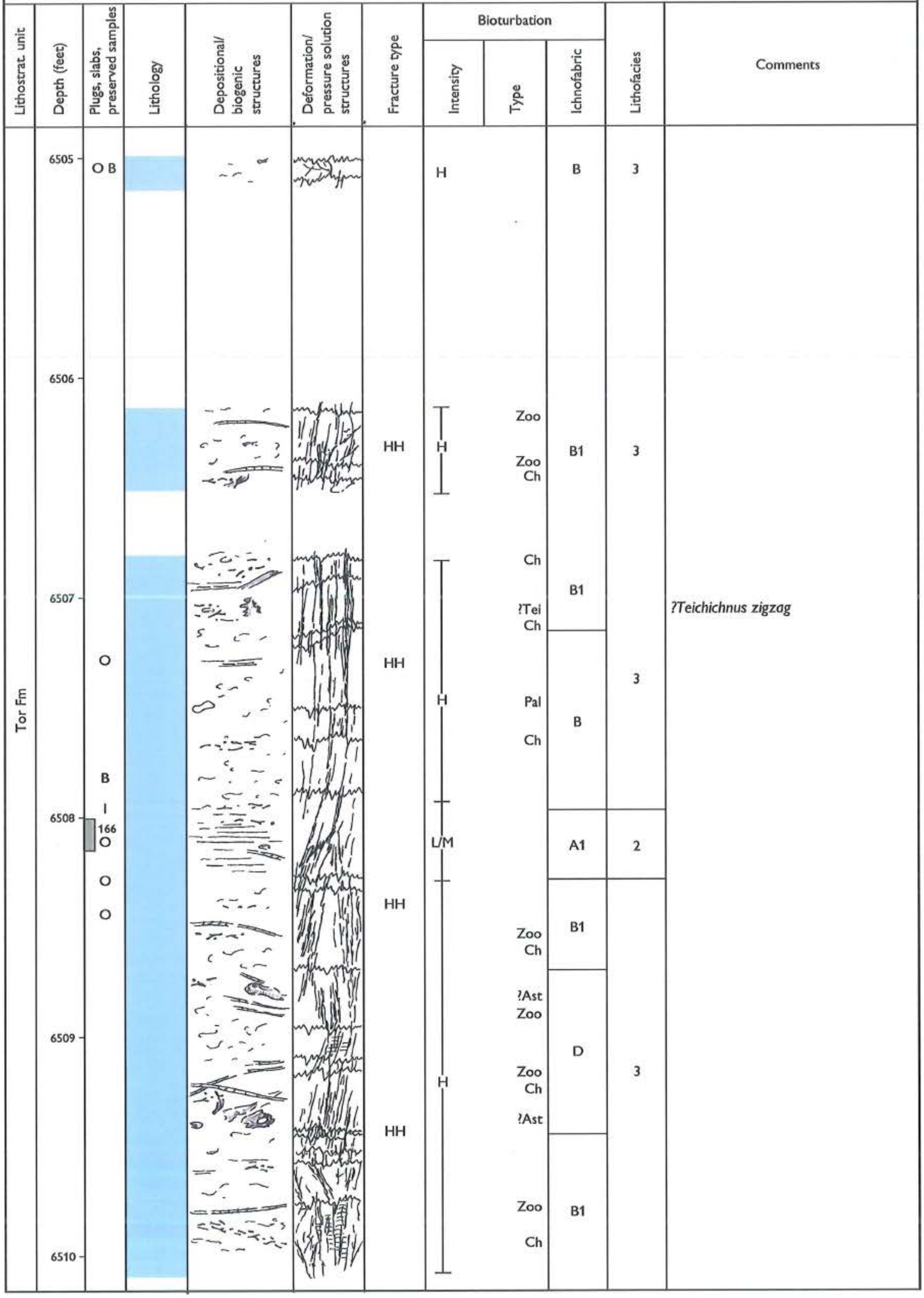
Lamination v. regular, spaced at 2–3 mm intervals

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 5

Scale : c 1:10
Geologist / Logging date : Jl, 3/2002

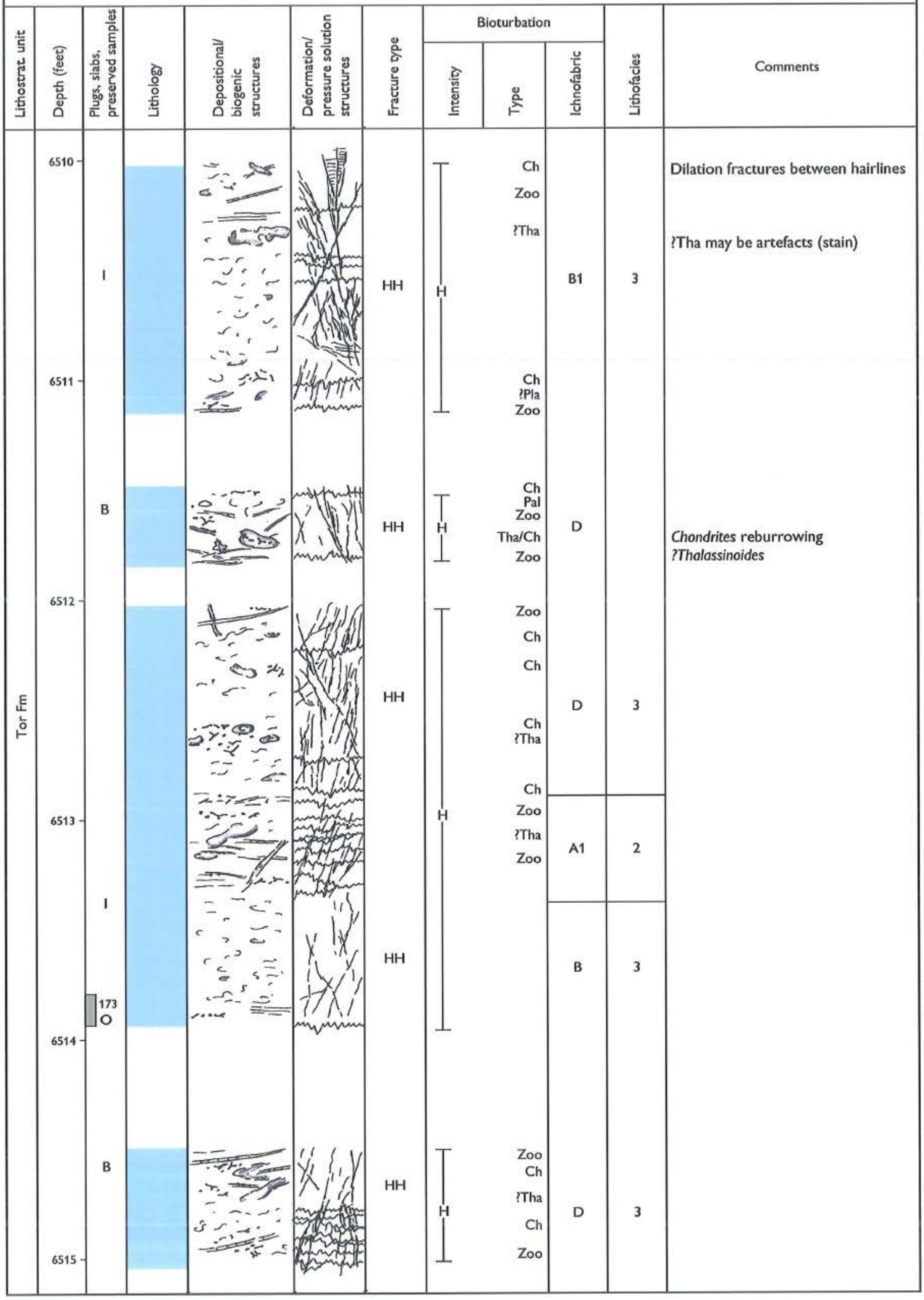


CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 5

Scale : c 1:10
Geologist / Logging date : Jl, 3/2002



Dilation fractures between hairlines

?Tha may be artefacts (stain)

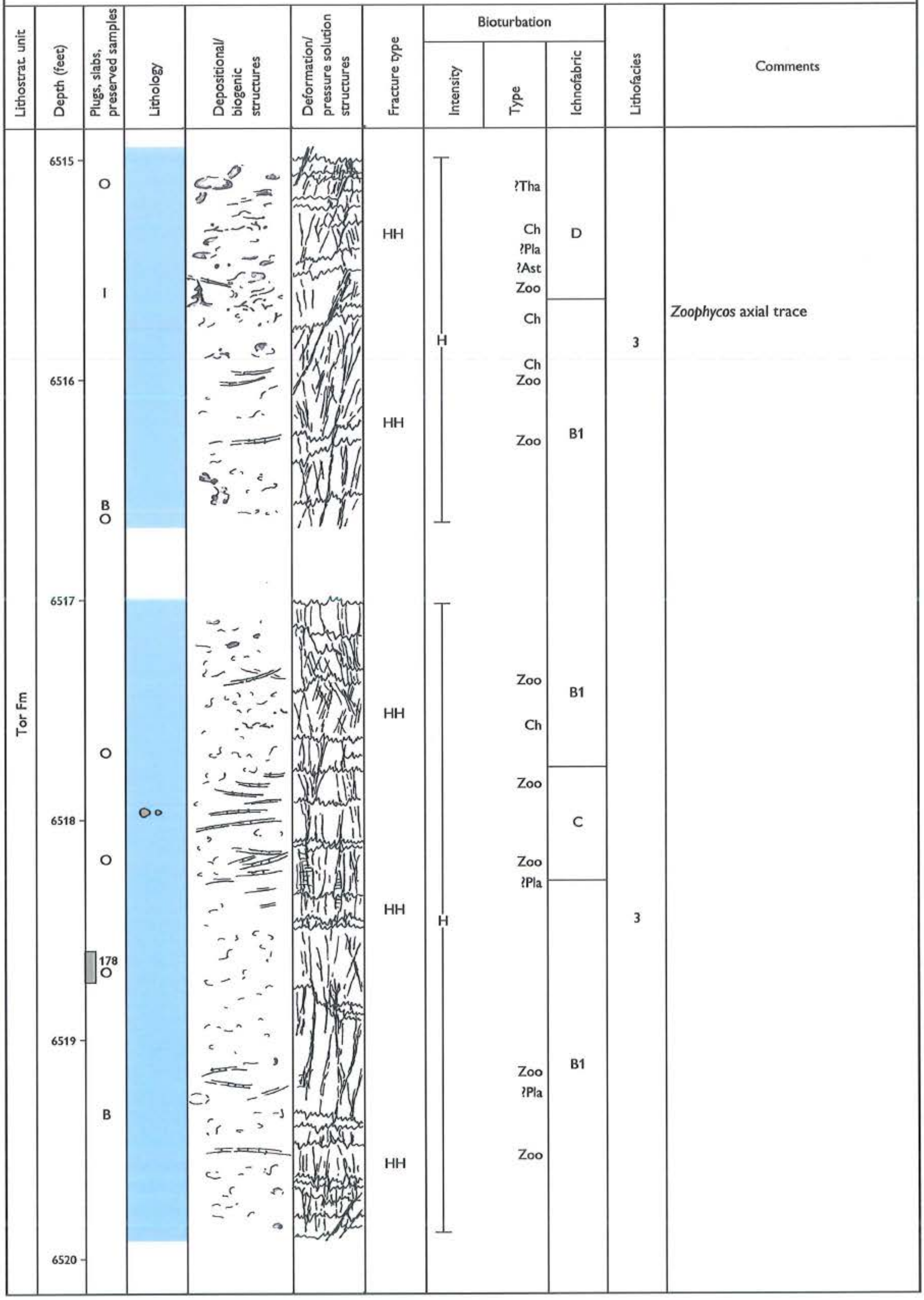
Chondrites reburrowing
?Thalassinoides

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 5

Scale : c 1:10
Geologist / Logging date : Jl, 3/2002

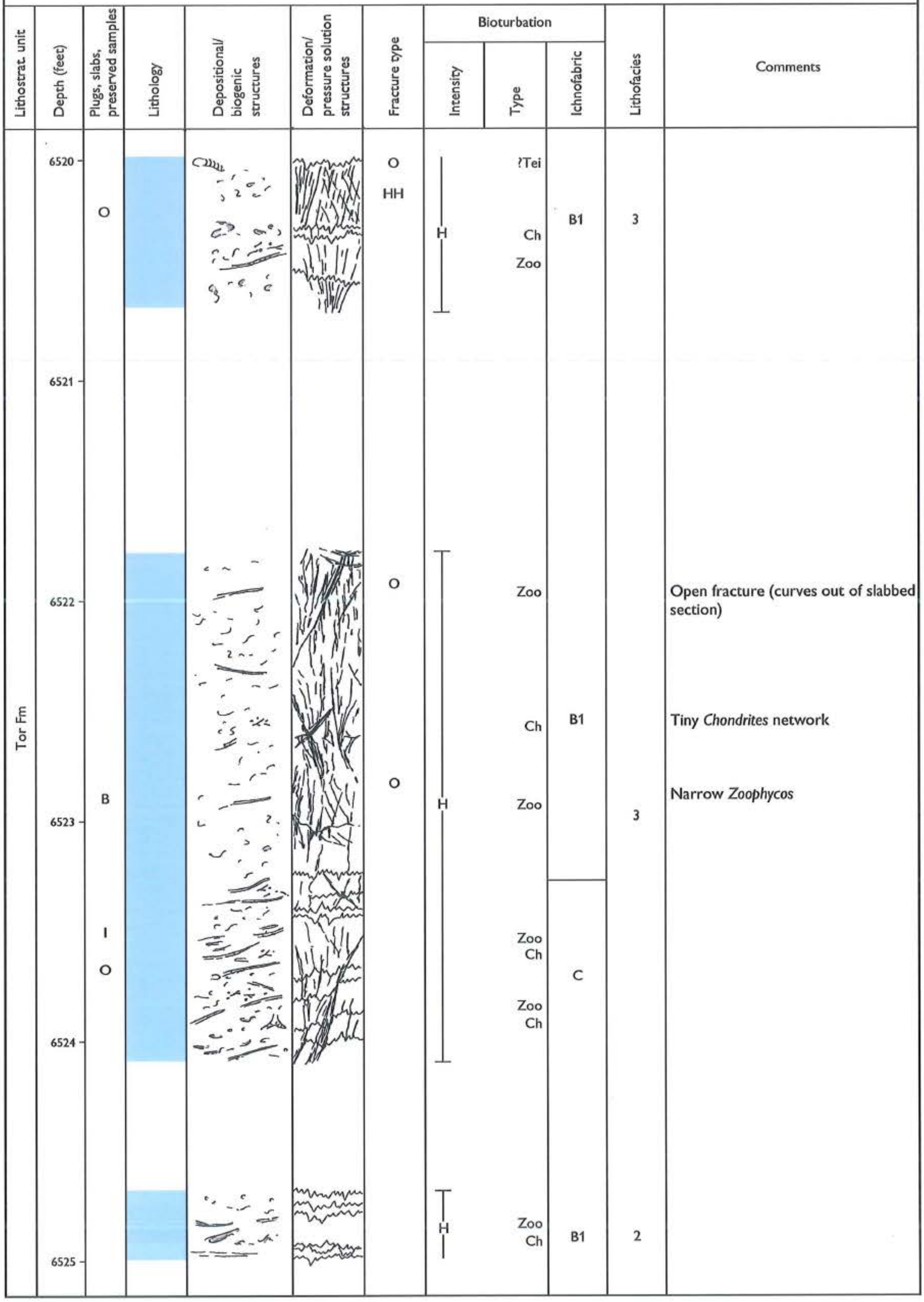


CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 5

Scale : c 1:10
Geologist / Logging date : Jl, 3/2002



Open fracture (curves out of slabbed section)

Tiny *Chondrites* network

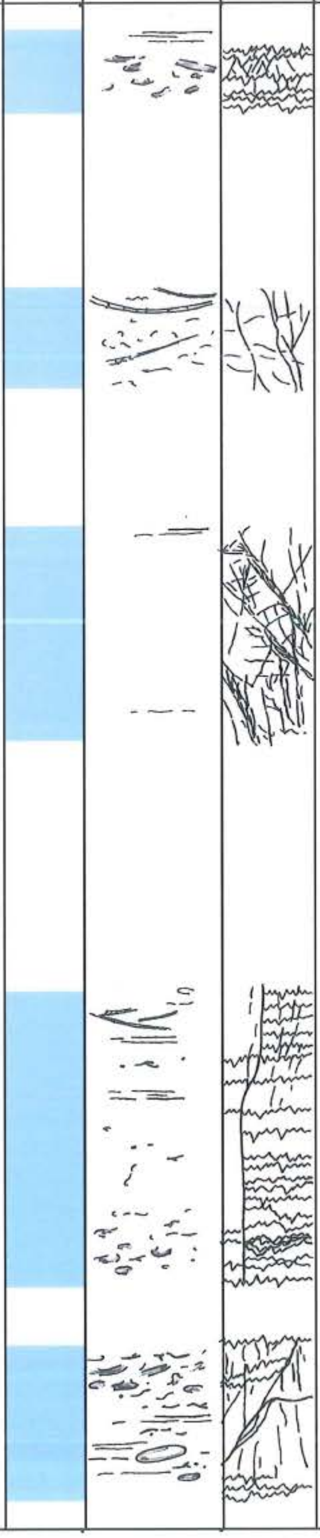
Narrow *Zoophycos*

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 5

Scale : c 1:10
Geologist / Logging date : Jl, 3/2002



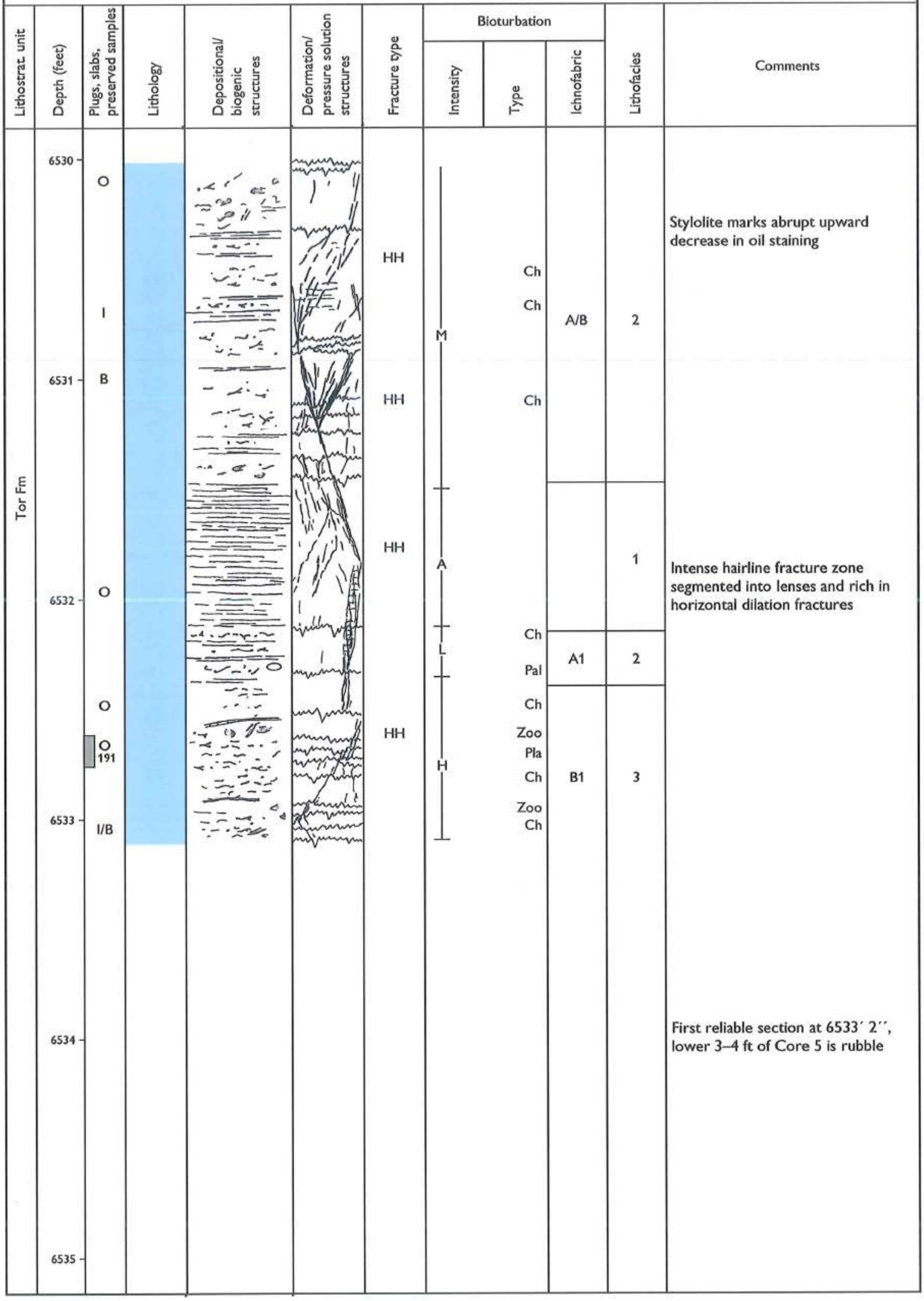
Lithostrat. unit	Depth (feet)	Plugs, slabs, preserved samples	Fracture type	Bioturbation			Lithofacies	Comments
				Intensity	Type	Ichnofabric		
Tor Fm	6525	O I	HH	H	?Pla	B	2	
	6526	I O O	HH	H	Zoo Zoo	B1	3	
	6527	186 O	HH	H		B	3	
	6528							
			O	M	Zoo	A1	2	Sub-vertical open fracture – affects oil staining (i.e. not coring artefact)
	6529	B I	O	H		B	3	
			O	H	Ch ?Pla	B	3	
	6530			M	?Pla Ch	A1	2	

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 5

Scale : c 1:10
Geologist / Logging date : Jl, 3/2002



Stylolite marks abrupt upward decrease in oil staining

Intense hairline fracture zone segmented into lenses and rich in horizontal dilation fractures

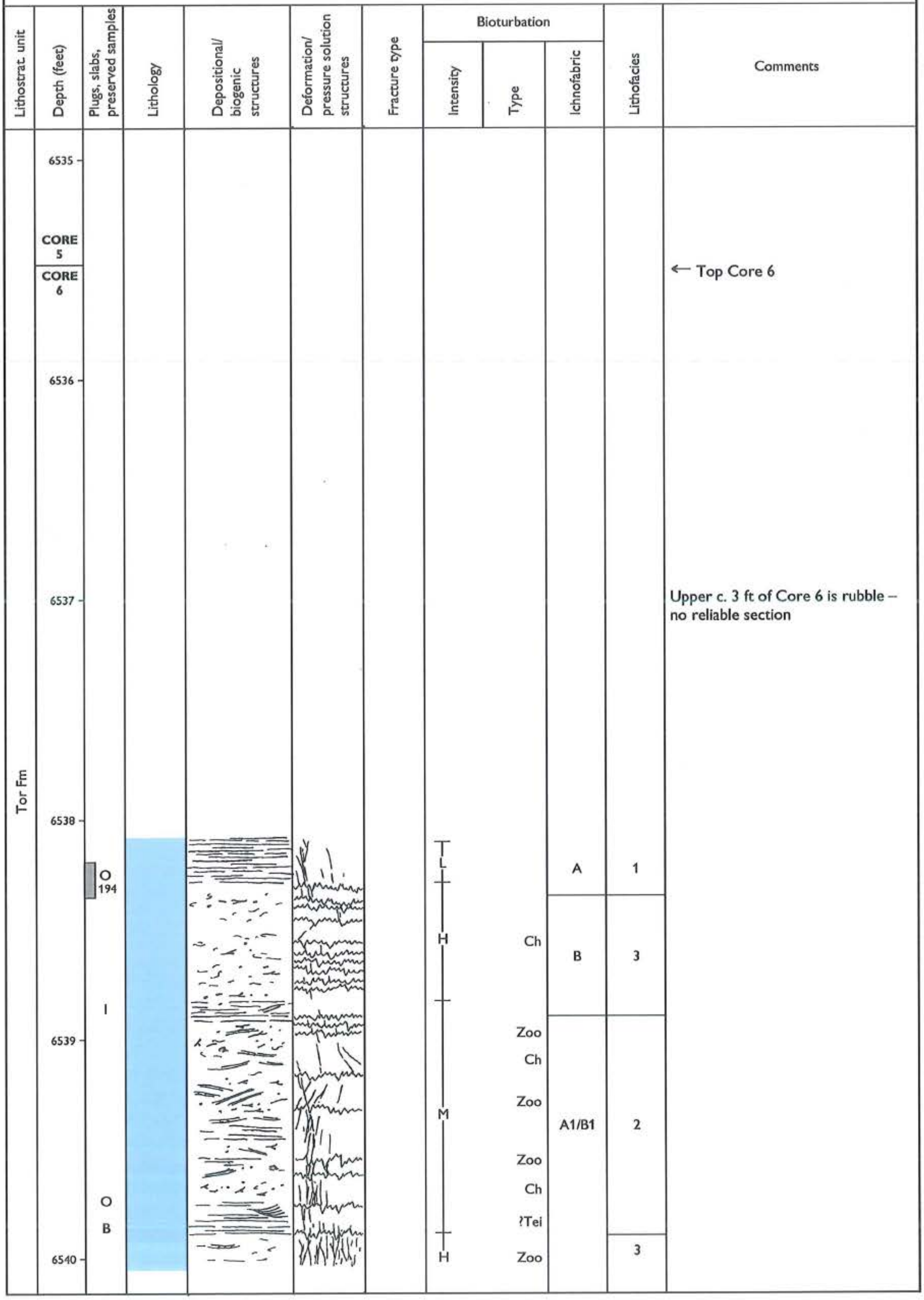
First reliable section at 6533′ 2′′, lower 3–4 ft of Core 5 is rubble

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 5/6

Scale : c 1:10
Geologist / Logging date : Jl, 2/2002



← Top Core 6

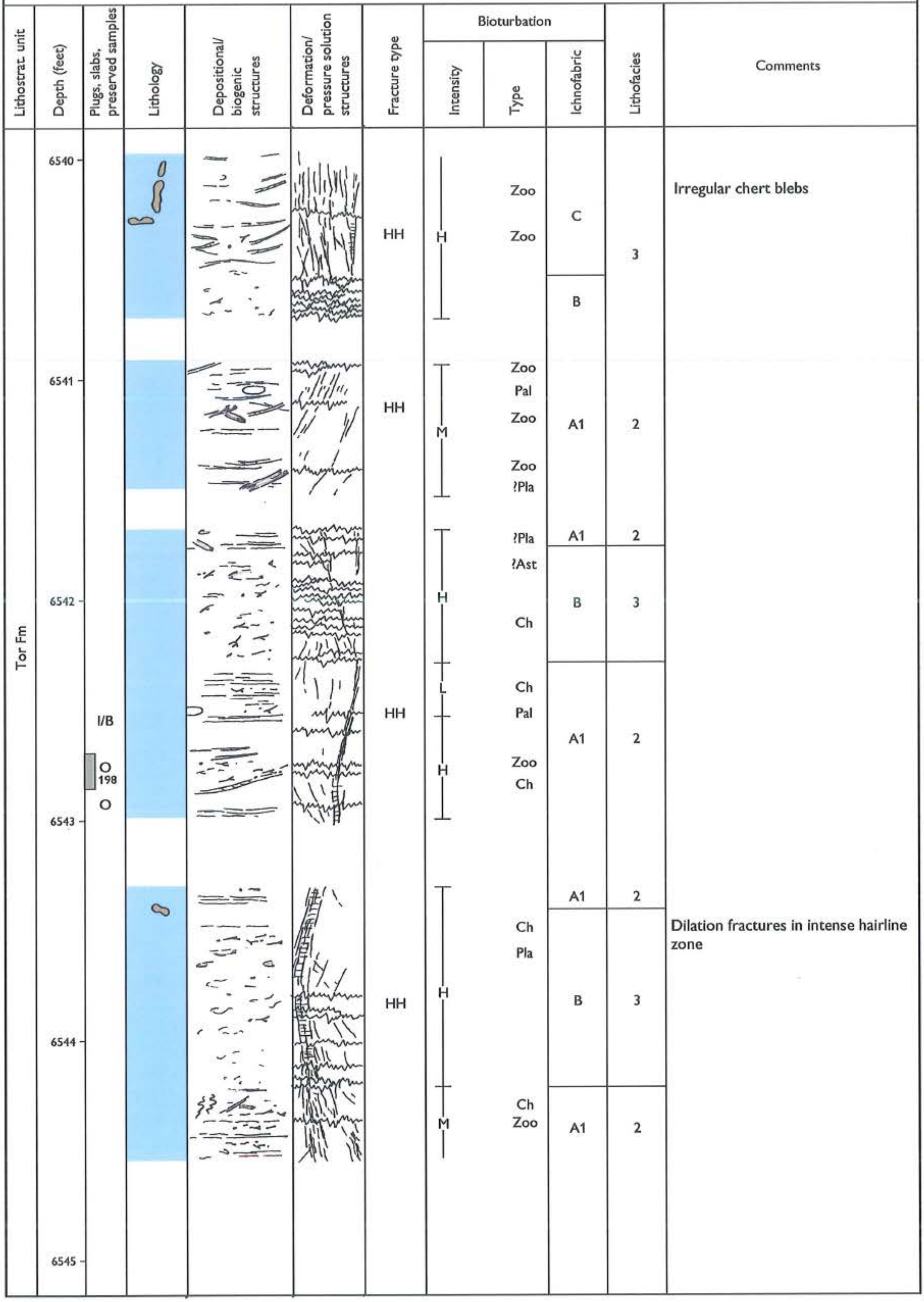
Upper c. 3 ft of Core 6 is rubble – no reliable section

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 6

Scale : c 1:10
Geologist / Logging date : Jl, 2/2002



Irregular chert blebs

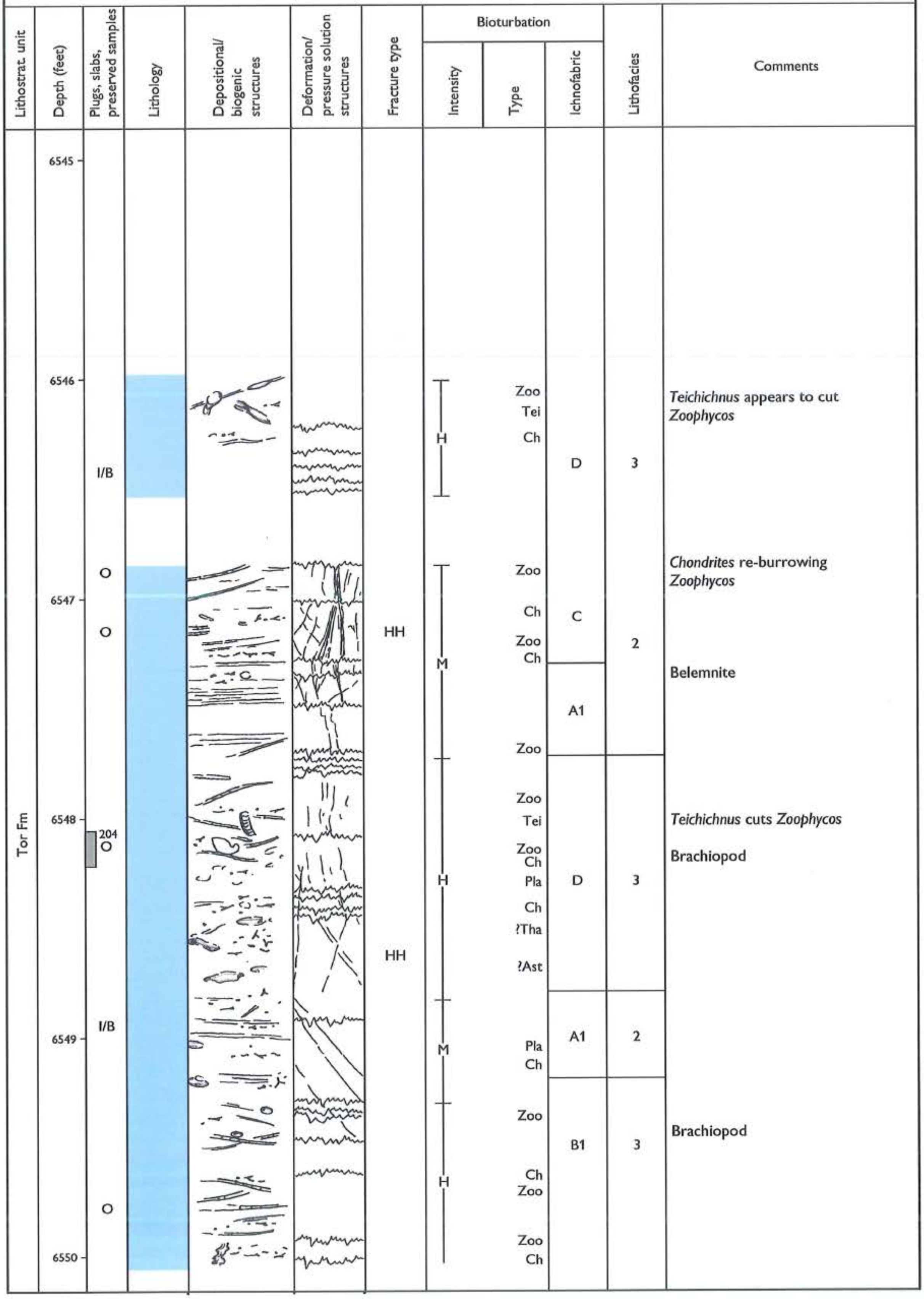
Dilation fractures in intense hairline zone

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 6

Scale : c 1:10
Geologist / Logging date : JI, 2/2002



Teichichnus appears to cut *Zoophycos*

Chondrites re-burrowing *Zoophycos*

Belemnite

Teichichnus cuts *Zoophycos*

Brachiopod

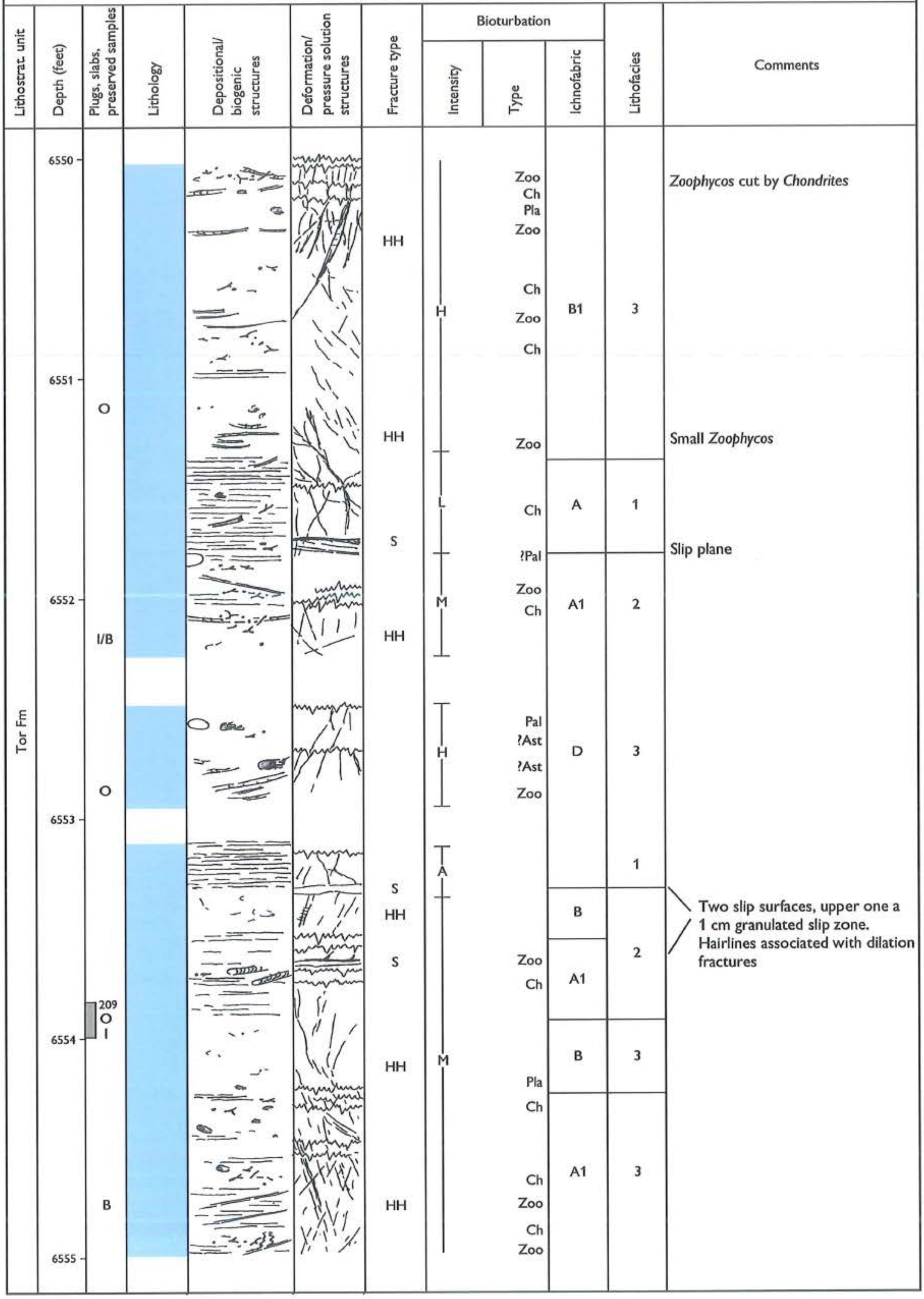
Brachiopod

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 6

Scale : c 1:10
Geologist / Logging date : JI, 2/2002



Zoophycos cut by *Chondrites*

Small *Zoophycos*

Slip plane

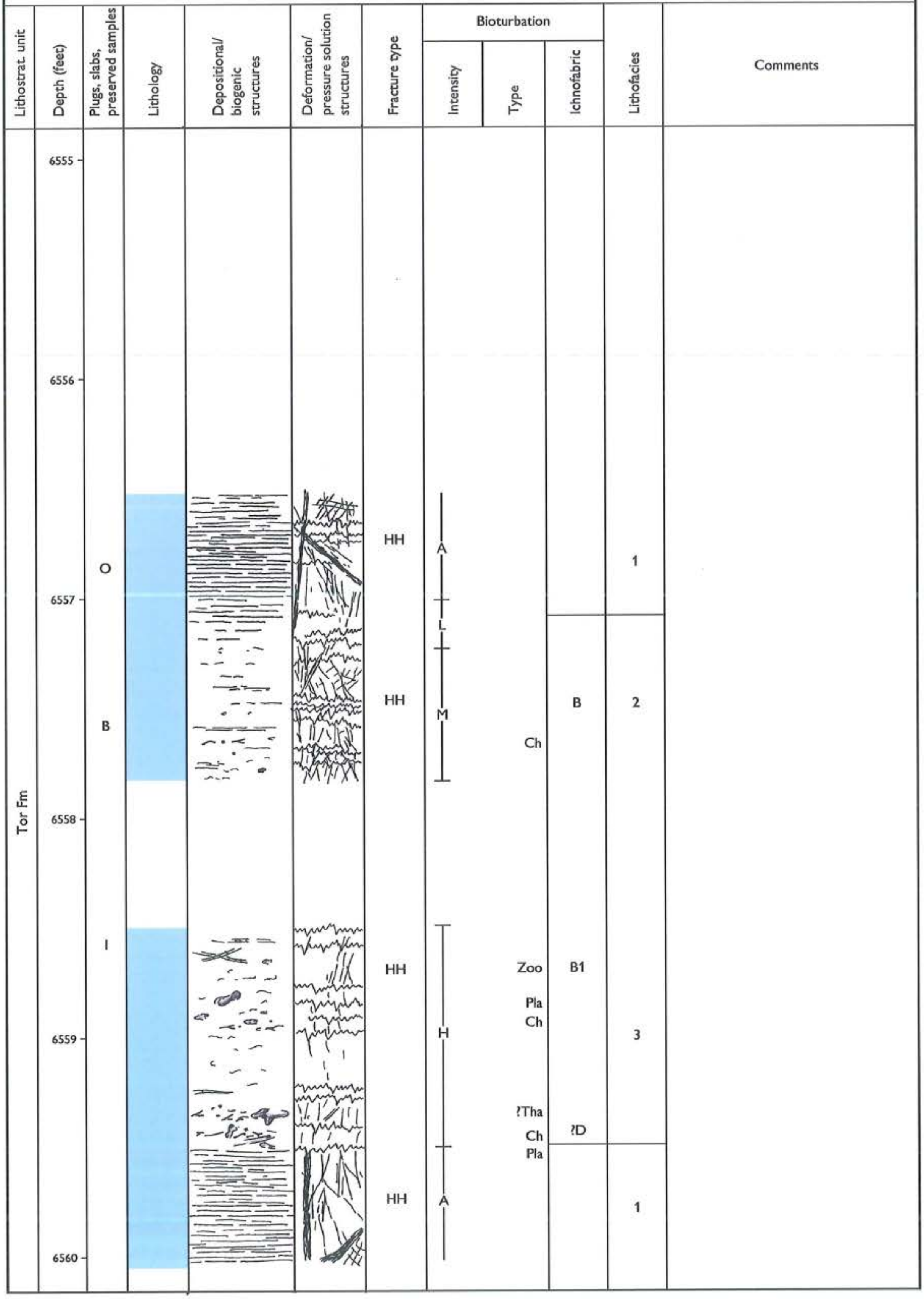
Two slip surfaces, upper one a 1 cm granulated slip zone. Hairlines associated with dilation fractures

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 6

Scale : c 1:10
Geologist / Logging date : Jl, 2/2002

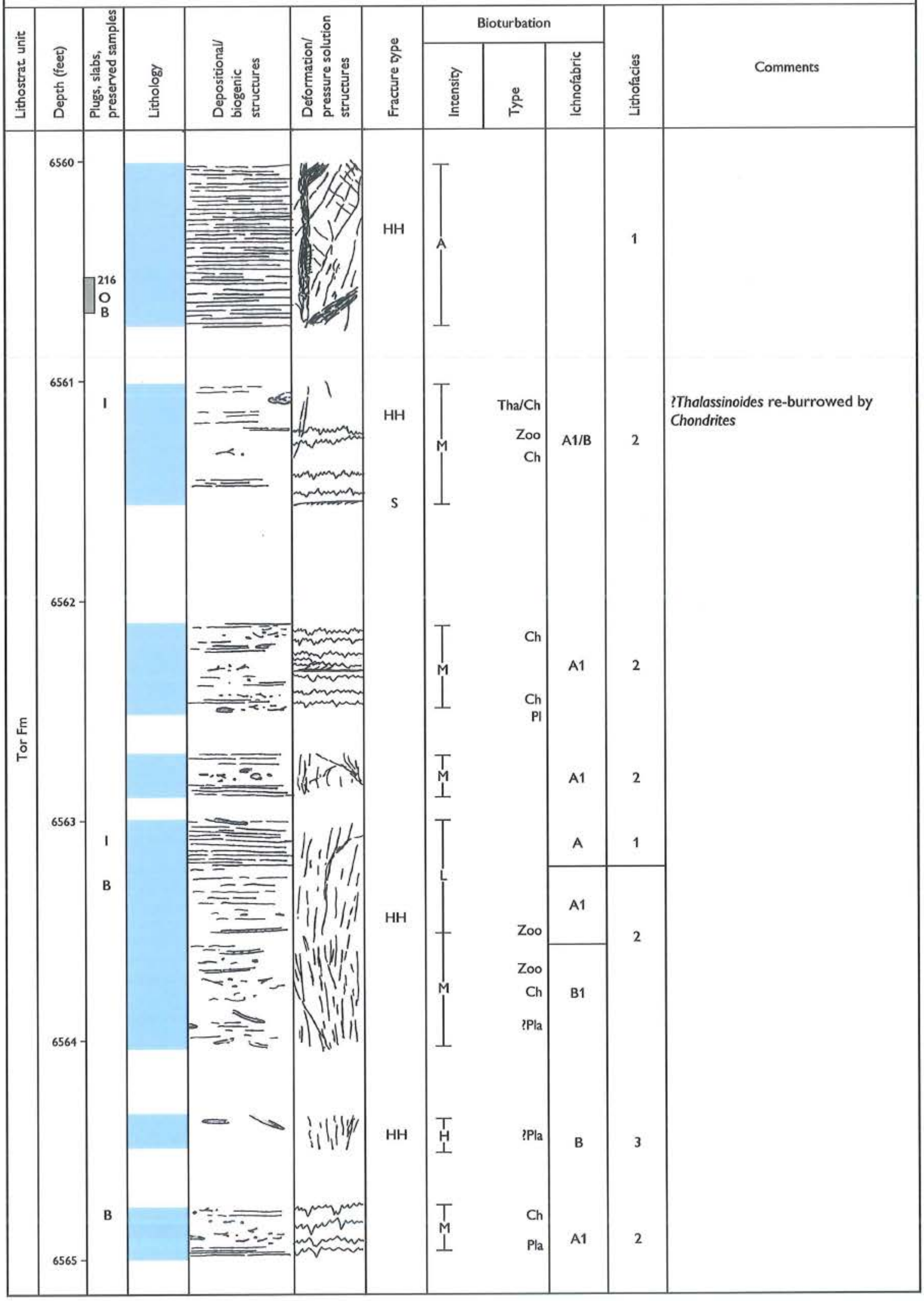


CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 6

Scale : c 1:10
Geologist / Logging date : JI, 2/2002



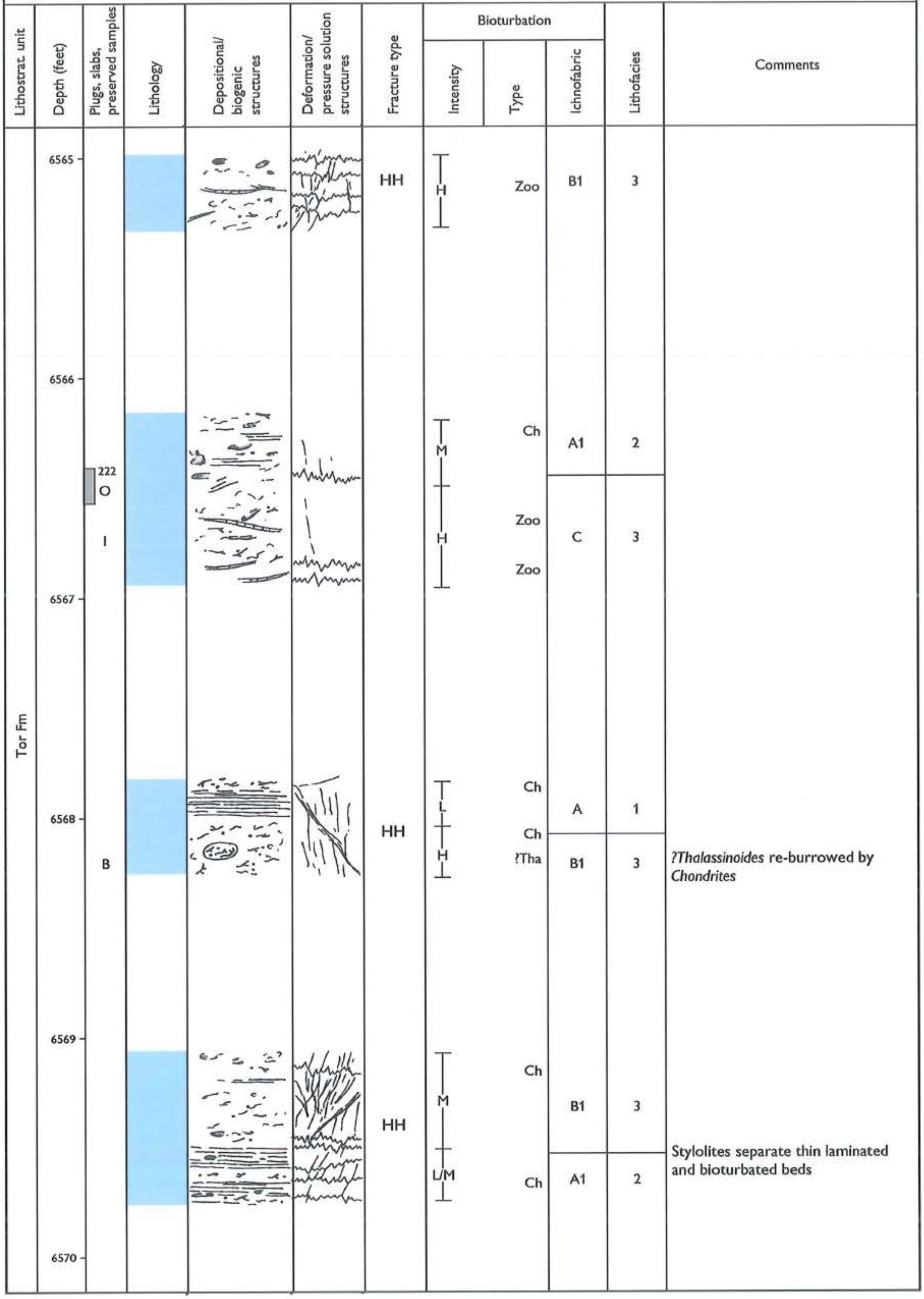
?Thalassinoides re-burrowed by *Chondrites*

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 6

Scale : c 1:10
Geologist / Logging date : Jl, 2/2002



?*Thalassinoides* re-burrowed by *Chondrites*

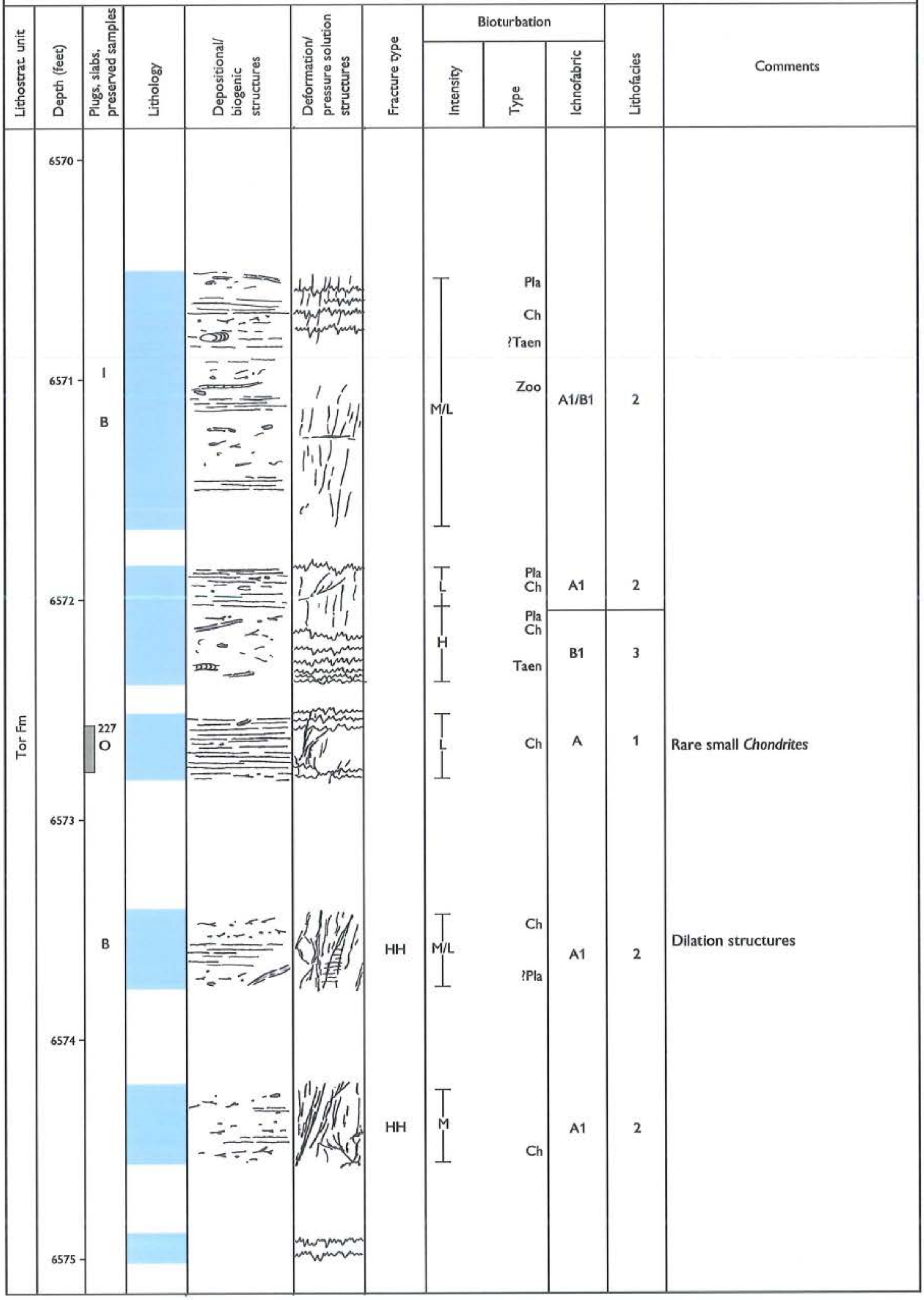
Stylolites separate thin laminated and bioturbated beds

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 6

Scale : c 1:10
Geologist / Logging date : Jl, 2/2002



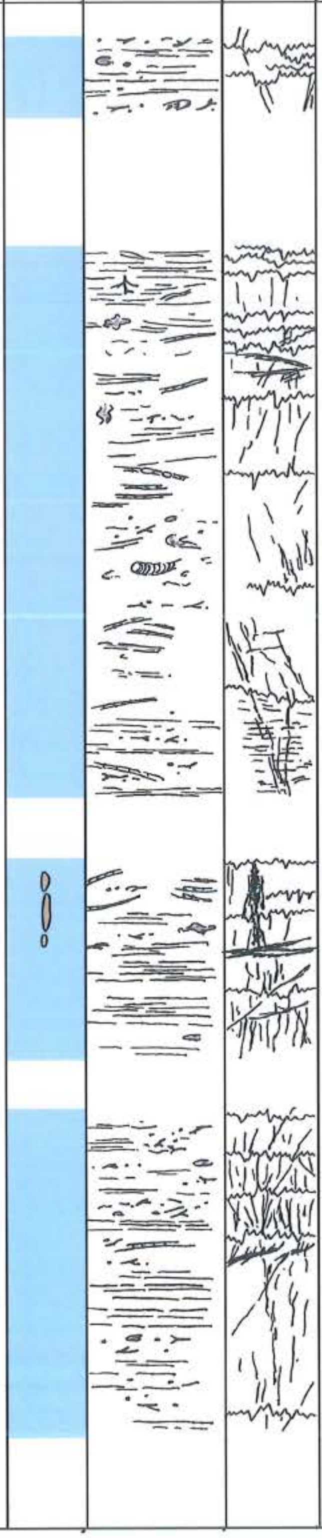
Lithostrat. unit	Depth (feet)	Plugs, slabs, preserved samples	Lithology	Depositional/ biogenic structures	Deformation/ pressure solution structures	Fracture type	Bioturbation Intensity	Bioturbation Type	Bioturbation Ichnofabric	Lithofacies	Comments
Tor Fm	6571	I B					M/L	Pla Ch ?Taen Zoo	A1/B1	2	
							L	Pla Ch	A1	2	
	6572						H	Pla Ch Taen	B1	3	
		227 O					L	Ch	A	1	Rare small *Chondrites*
	6573	B				HH	M/L	Ch ?Pla	A1	2	Dilation structures
	6574					HH	M	Ch	A1	2	

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 6

Scale : c 1:10
Geologist / Logging date : Jl, 2/2002



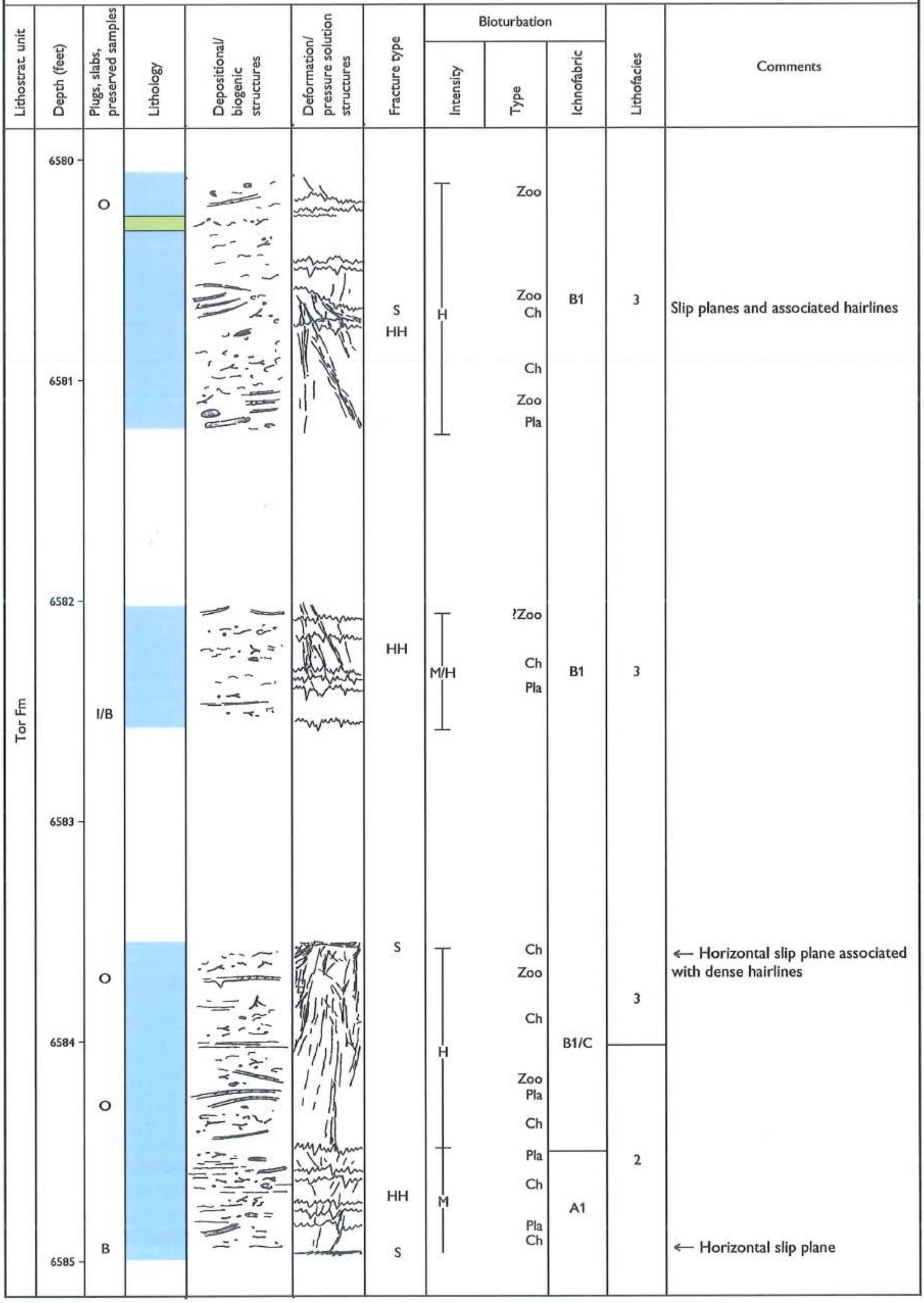
Lithostrat. unit	Depth (feet)	Plugs, slabs, preserved samples	Fracture type	Bioturbation: Intensity	Bioturbation: Type	Bioturbation: Ichnofabric	Lithofacies	Comments
Tor Fm	6575		HH	L/M	Ch ?Taen	A1	2	
	6576		S HH	L M	Ch Zoo ?Ast Ch	A1	2	Sub-horizontal slip planes, associated with hairlines
	6577	O I/B	HH	H	Zoo Ch Taen Zoo Zoo	D	3	Large *Chondrites* within *Zoophycos* Horizontal dilation fractures
				M	Ch Zoo	A1	2	
	6578		HH	M L	Zoo ?Ast Pla	A1	1	Chert blebs along vertical fracture zone
	6579	I O 234 B	HH	L/M	Ch Ch Zoo Ch Ch	A1	2	
	6580							

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 6

Scale : c 1:10
Geologist / Logging date : Jl, 2/2002

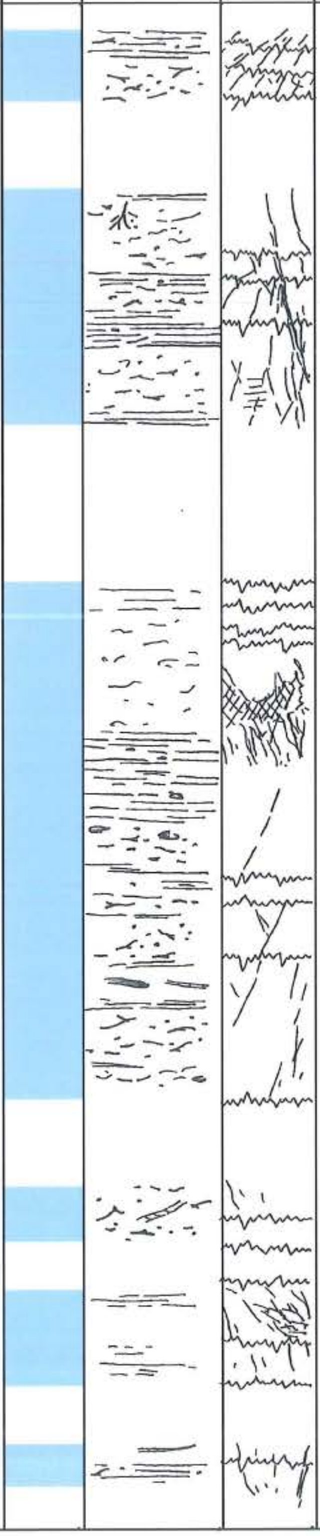


CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 6

Scale : c 1:10
Geologist / Logging date : JI, 2/2002



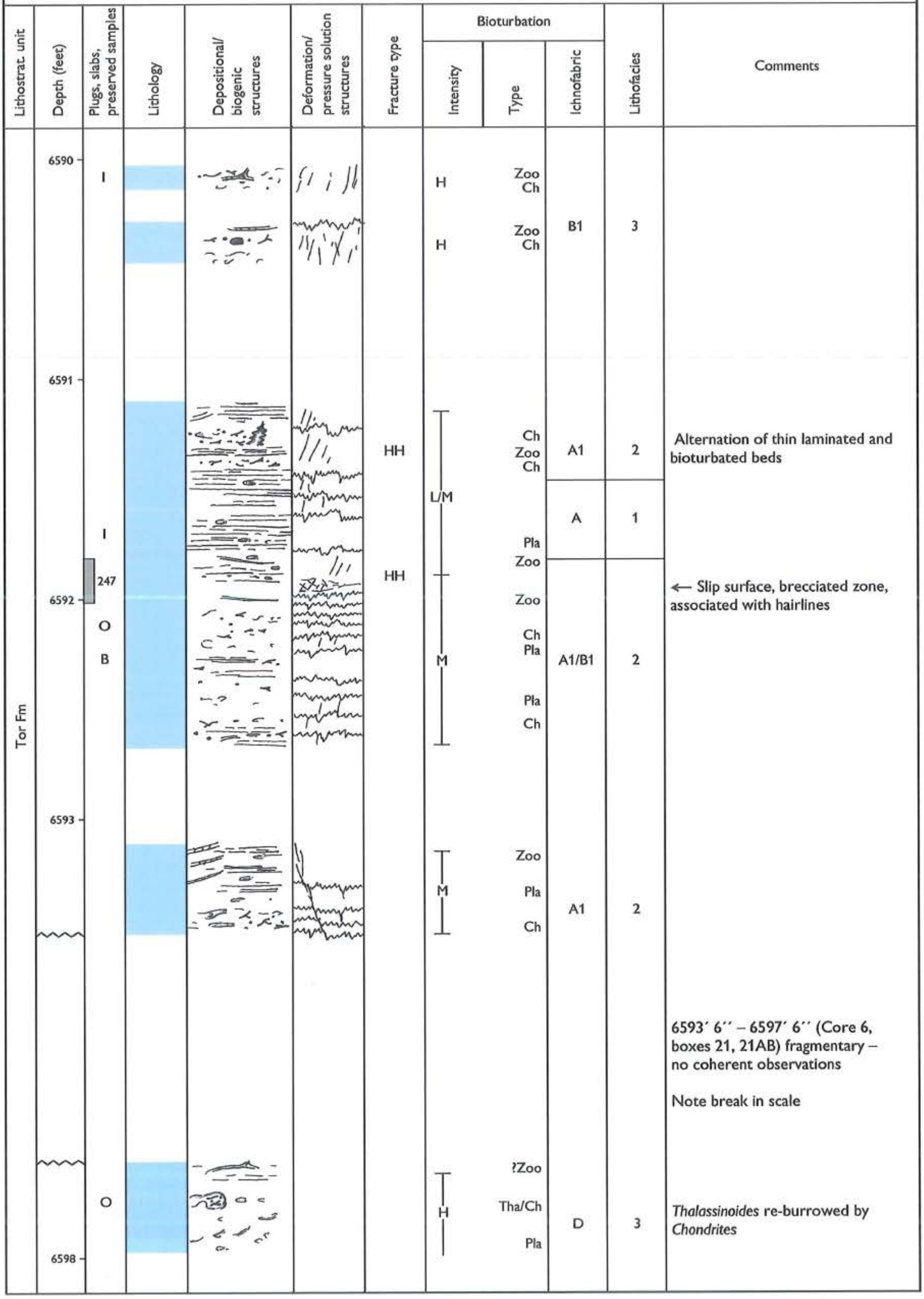
Lithostrat. unit	Depth (feet)	Plugs, slabs, preserved samples	Fracture type	Bioturbation Intensity	Bioturbation Type	Bioturbation Ichnofabric	Lithofacies	Comments
Tor Fm	6585		HH	M H	Ch	A1/B1	2	
					Ch			
	6586		HH	M/L		A1/B1	2	
		241 O I B			Ch			Horizontal dilation hairline structures associated with sub-vertical hairlines
	6587							
						B	2	
			HH					Brecciated zone – intense hairlines
						A	1	
				M/L	Ch Pla			
	6588				Ch	A1	2	
		O			Zoo Pla Ch			
					Ch	B1	3	
	6589			H	Ch Zoo	B1	3	
				M		A1	2	
	6590	B		H	?Zoo	A1	2	

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 6/7

Scale : c 1:10
Geologist / Logging date : JI, 2/2002



Alternation of thin laminated and bioturbated beds

← Slip surface, brecciated zone, associated with hairlines

6593′ 6′′ – 6597′ 6′′ (Core 6, boxes 21, 21AB) fragmentary – no coherent observations

Note break in scale

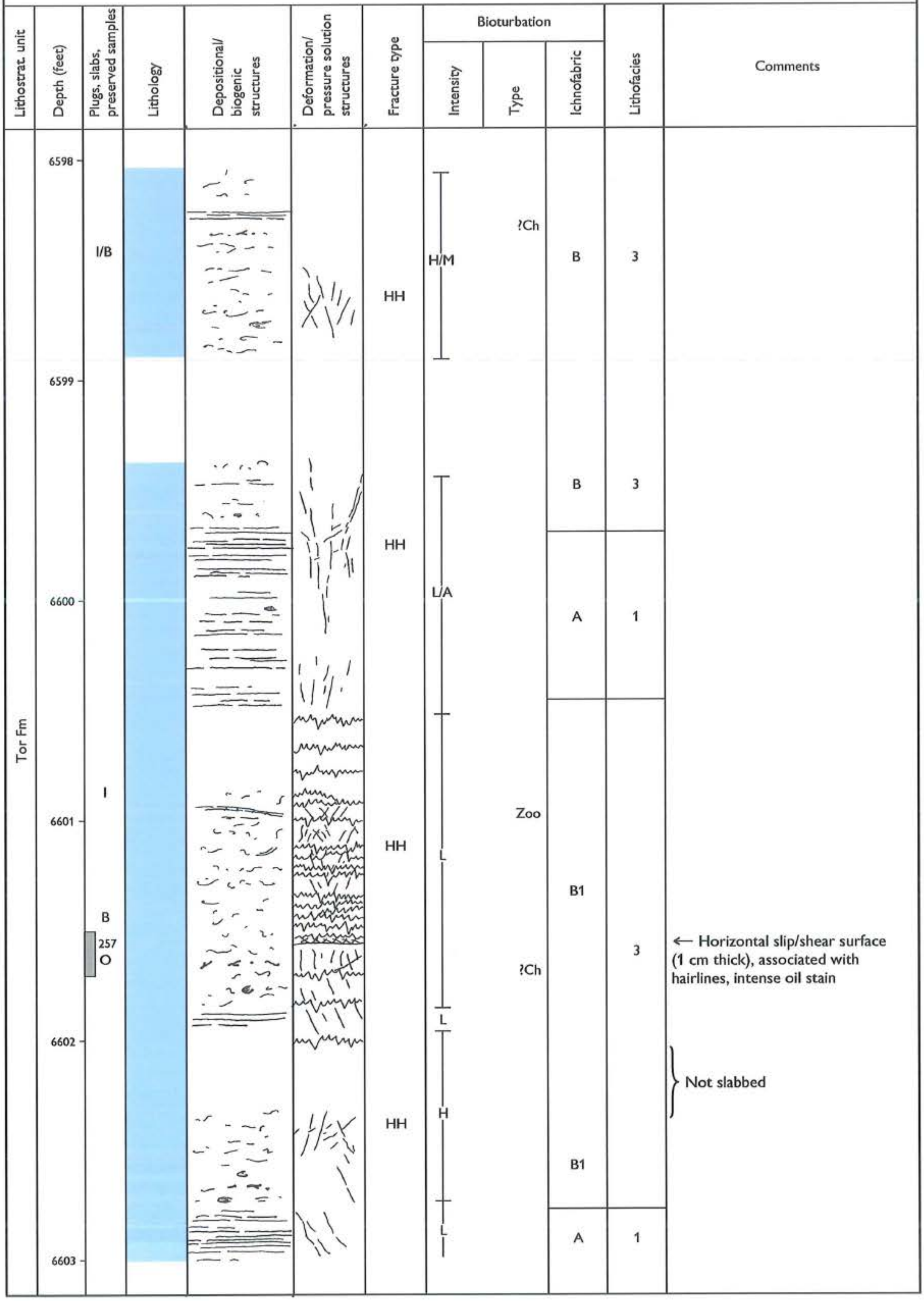
Thalassinoides re-burrowed by *Chondrites*

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 7

Scale : c 1:10
Geologist / Logging date : Jl, 2/2002



← Horizontal slip/shear surface (1 cm thick), associated with hairlines, intense oil stain

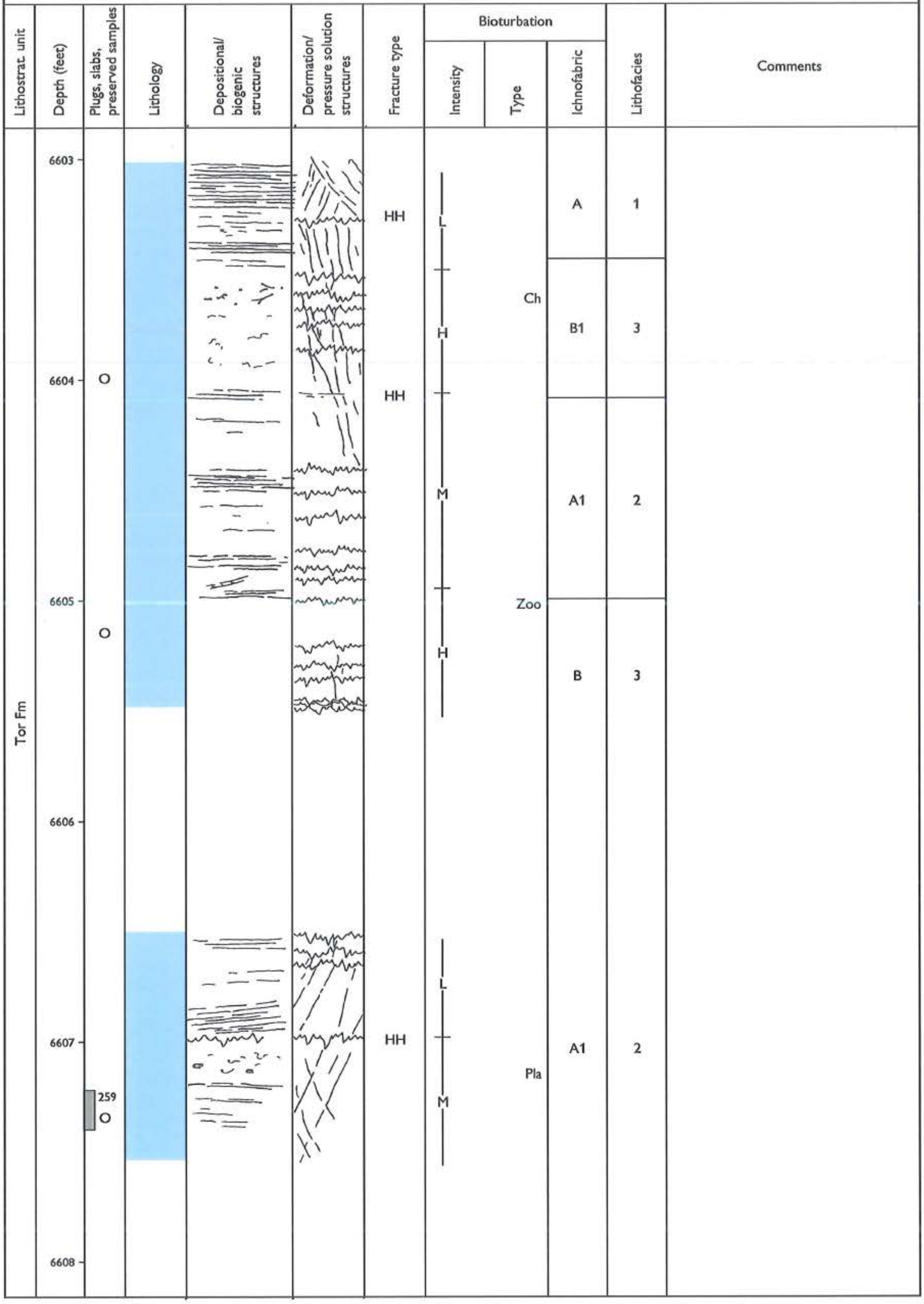
} Not slabbed

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 7

Scale : c 1:10
Geologist / Logging date : Jl, 2/2002

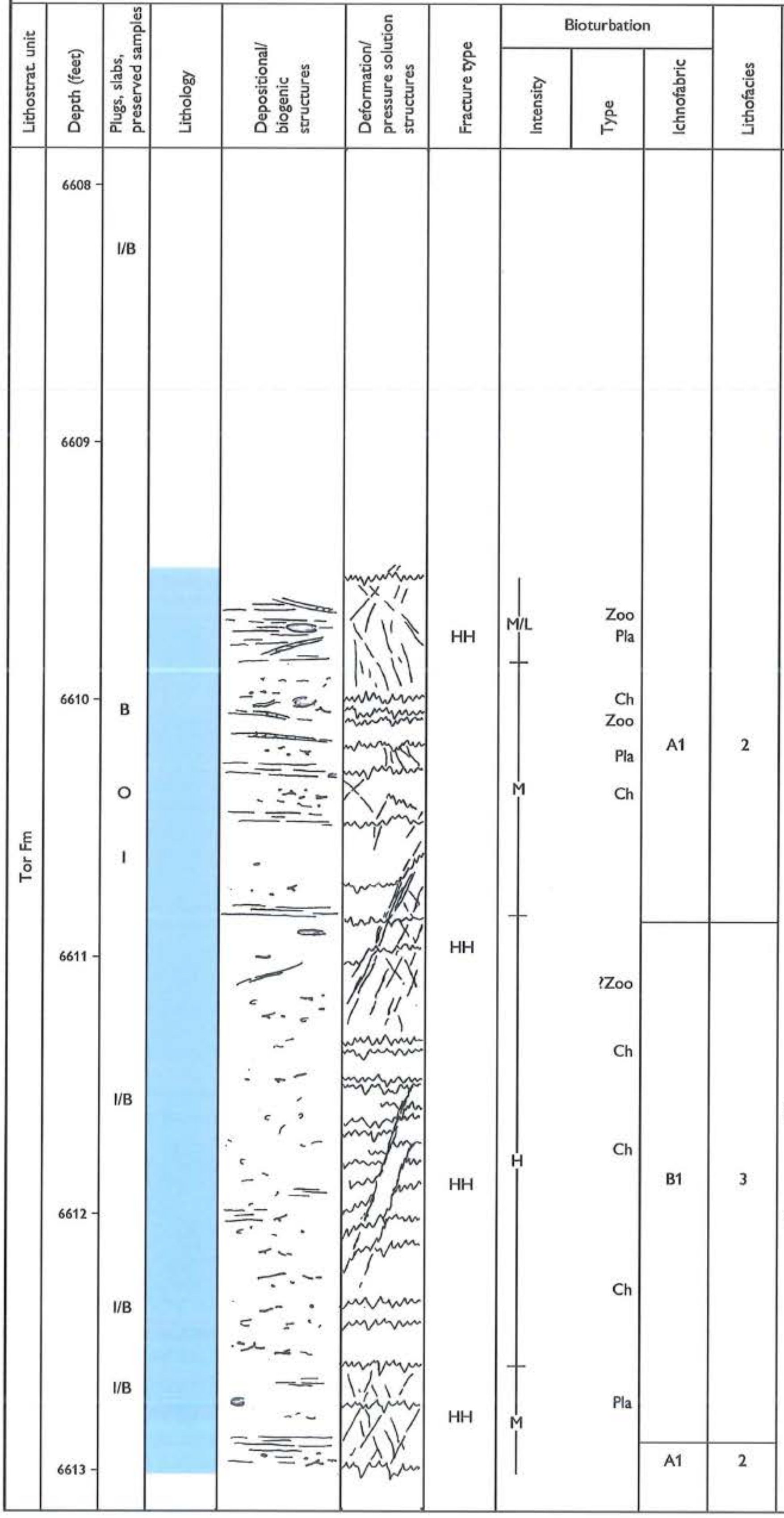


CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 7

Scale : c 1:10
Geologist / Logging date : Jl, 2/2002



Comments

Note – sample from rubble zone i.e. within interval 6607′ 7′′ – 6609′ 6′′

Stylolites follow earlier hairlines

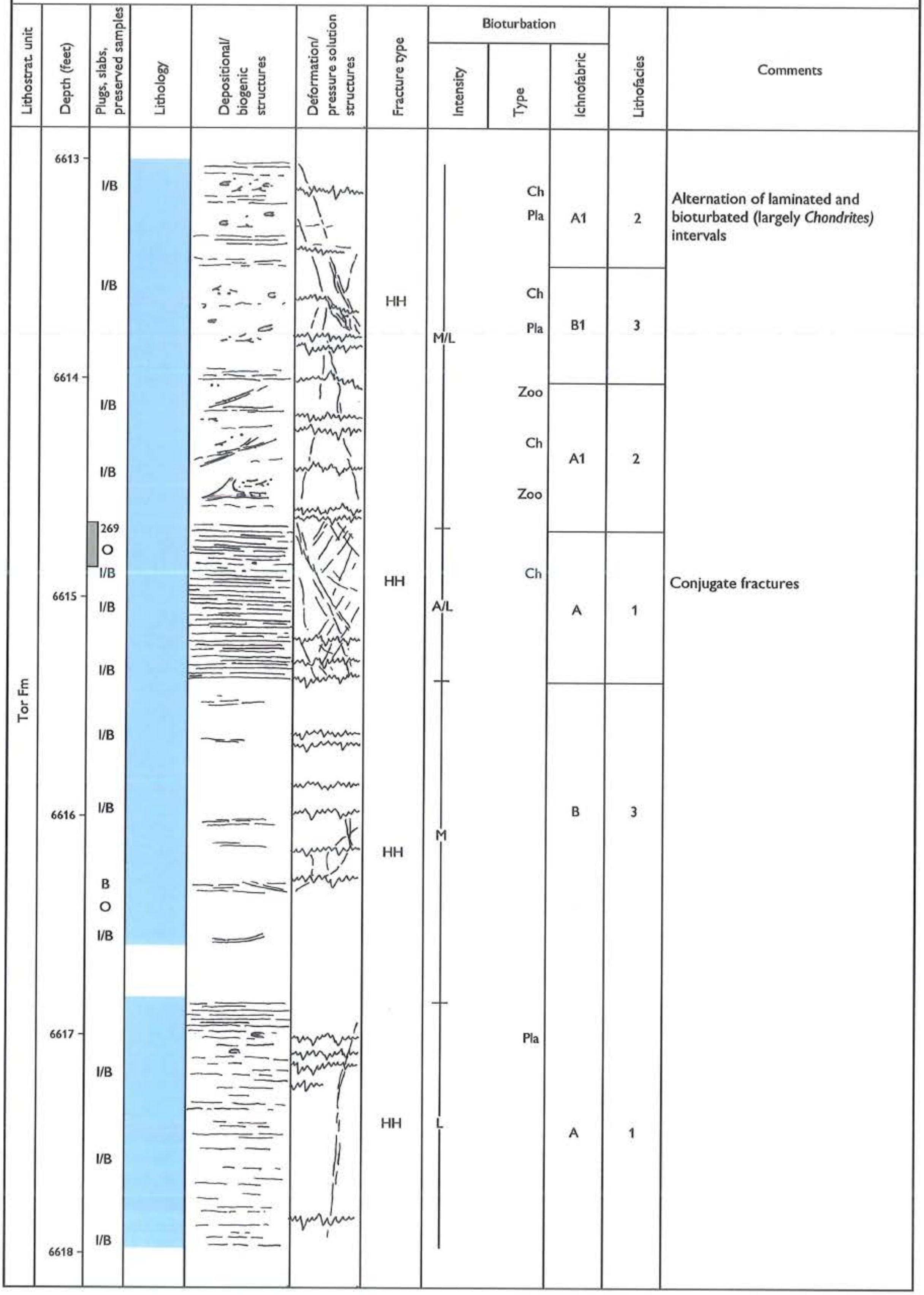
Rare vestiges of lamination

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 7

Scale : c 1:10
Geologist / Logging date : JI, 2/2002



Alternation of laminated and bioturbated (largely *Chondrites*) intervals

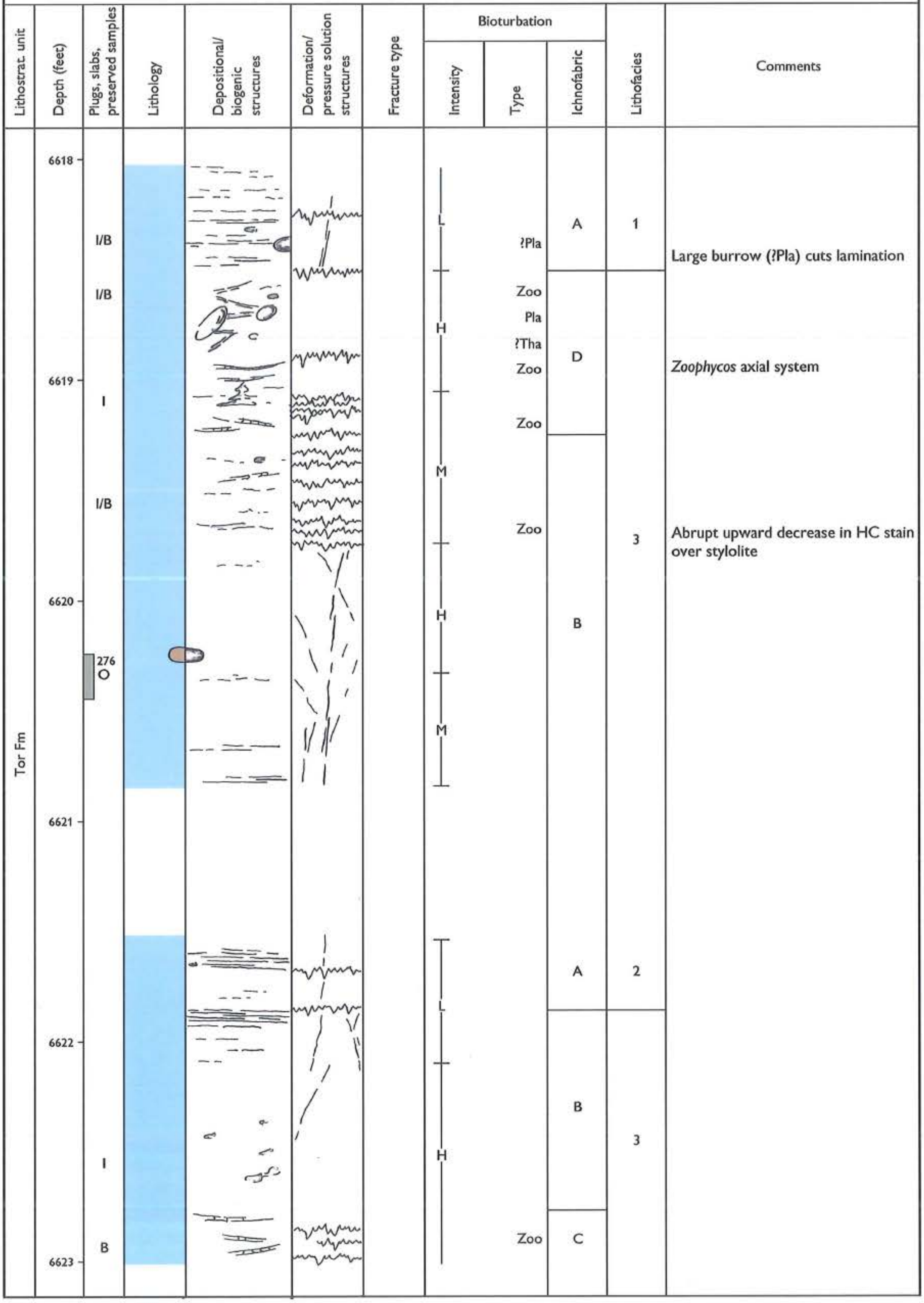
Conjugate fractures

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 7

Scale : c 1:10
Geologist / Logging date : Jl, 2/2002



Large burrow (?Pla) cuts lamination

Zoophycos axial system

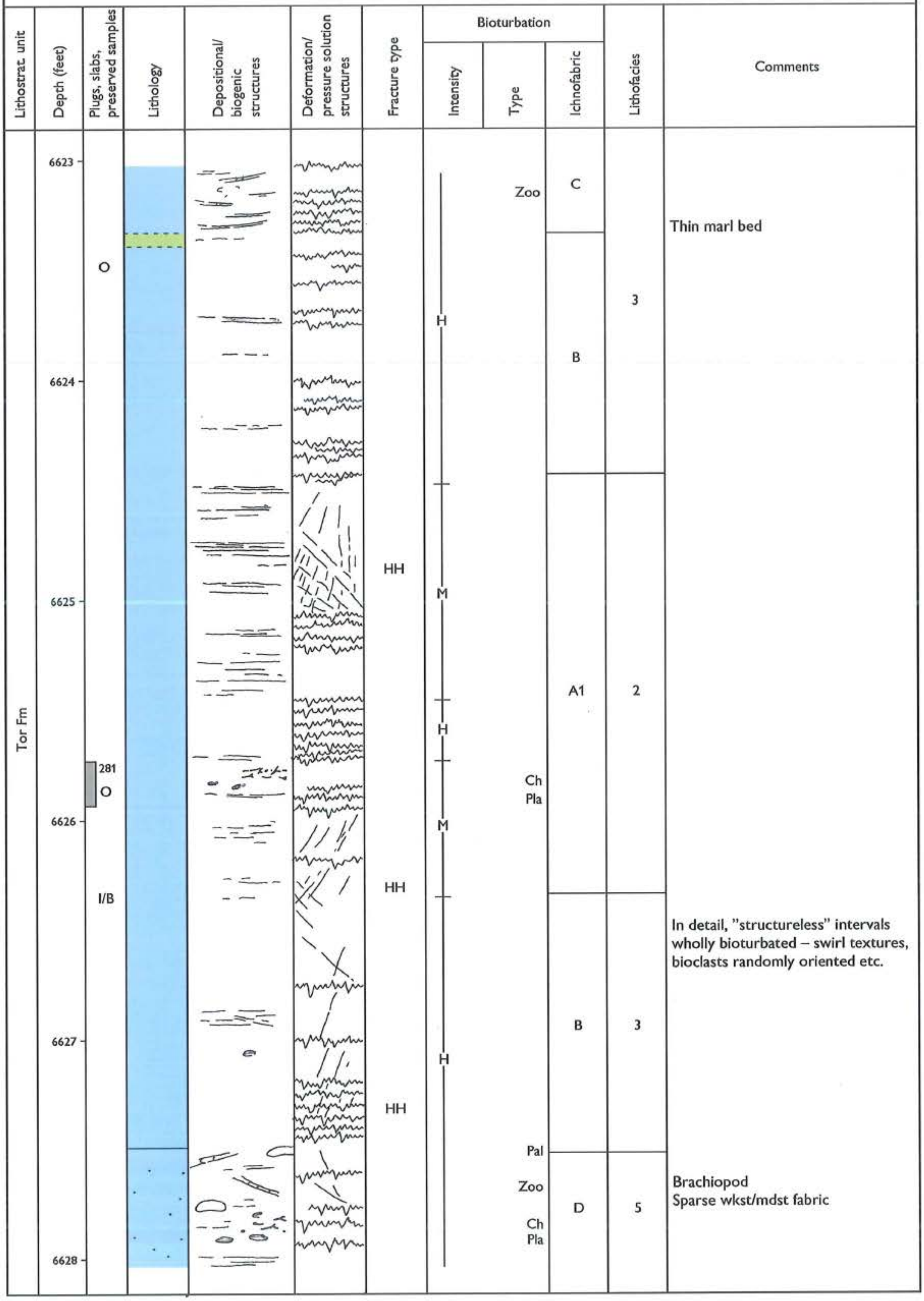
Abrupt upward decrease in HC stain over stylolite

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 7

Scale : c 1:10
Geologist / Logging date : JI, 2/2002



Thin marl bed

In detail, "structureless" intervals wholly bioturbated – swirl textures, bioclasts randomly oriented etc.

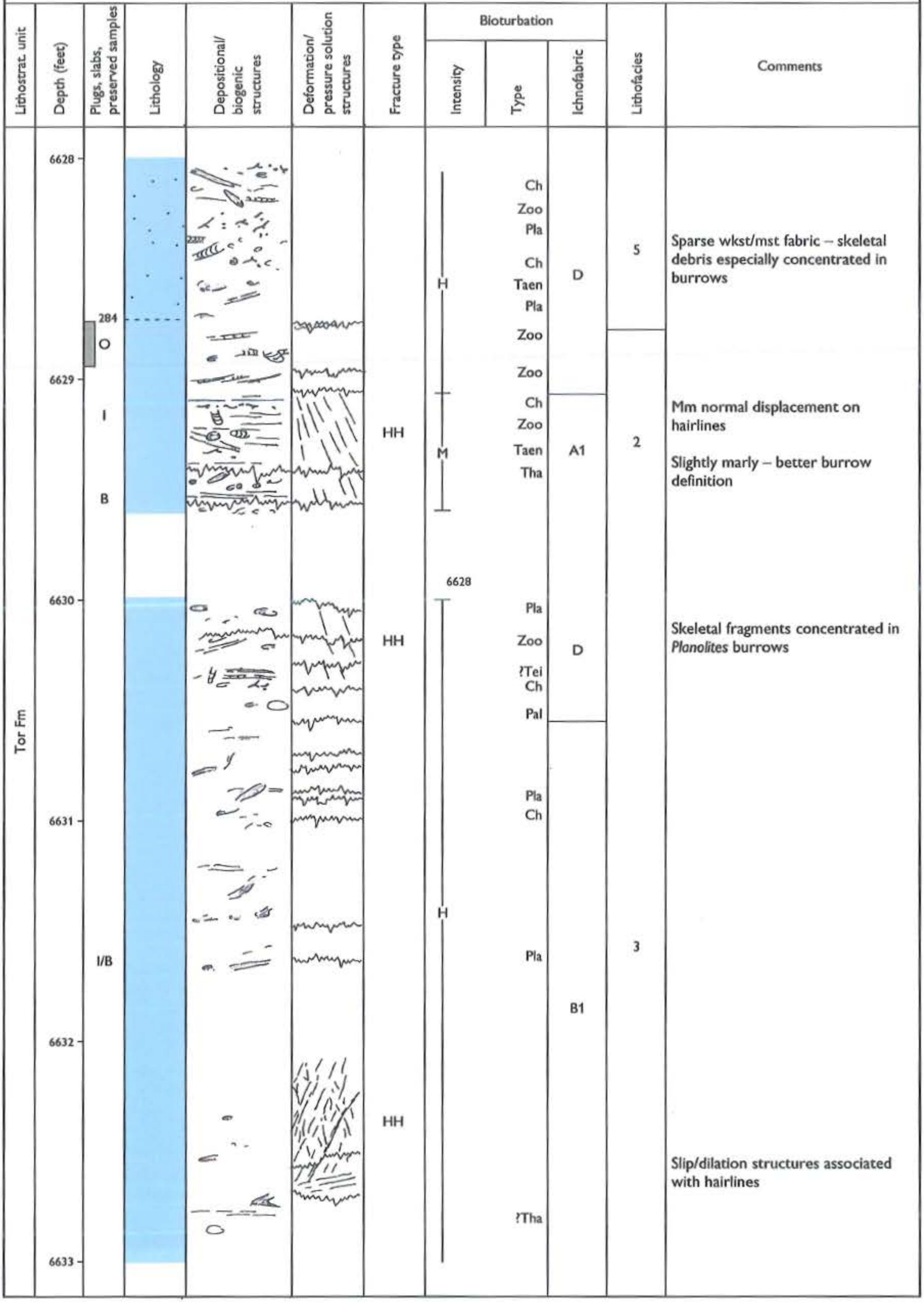
Brachiopod
Sparse wkst/mdst fabric

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 7

Scale : c 1:10
Geologist / Logging date : JI, 2/2002



Sparse wkst/mst fabric – skeletal debris especially concentrated in burrows

Mm normal displacement on hairlines

Slightly marly – better burrow definition

Skeletal fragments concentrated in *Planolites* burrows

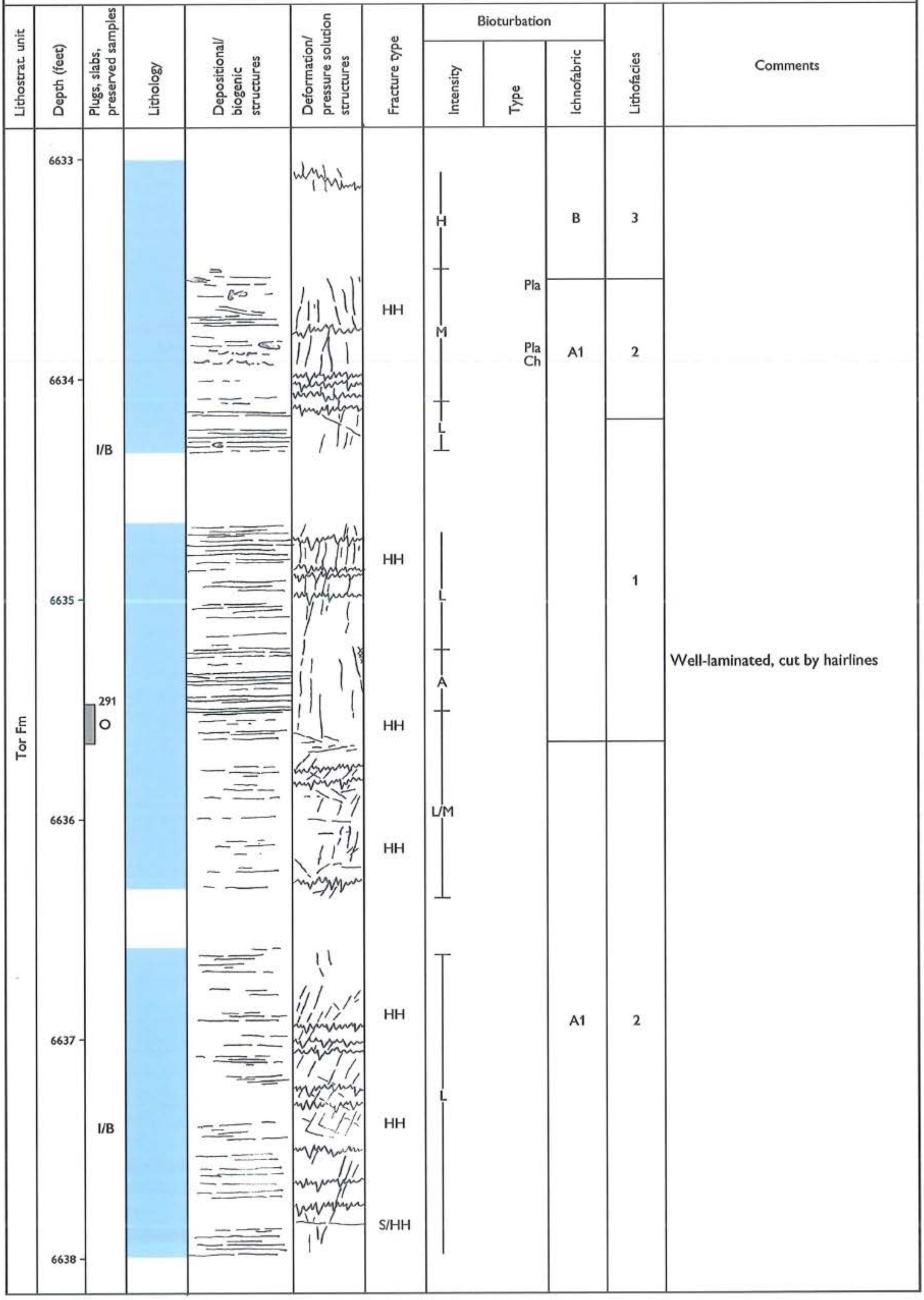
Slip/dilation structures associated with hairlines

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 7

Scale : c 1:10
Geologist / Logging date : Jl, 2/2002



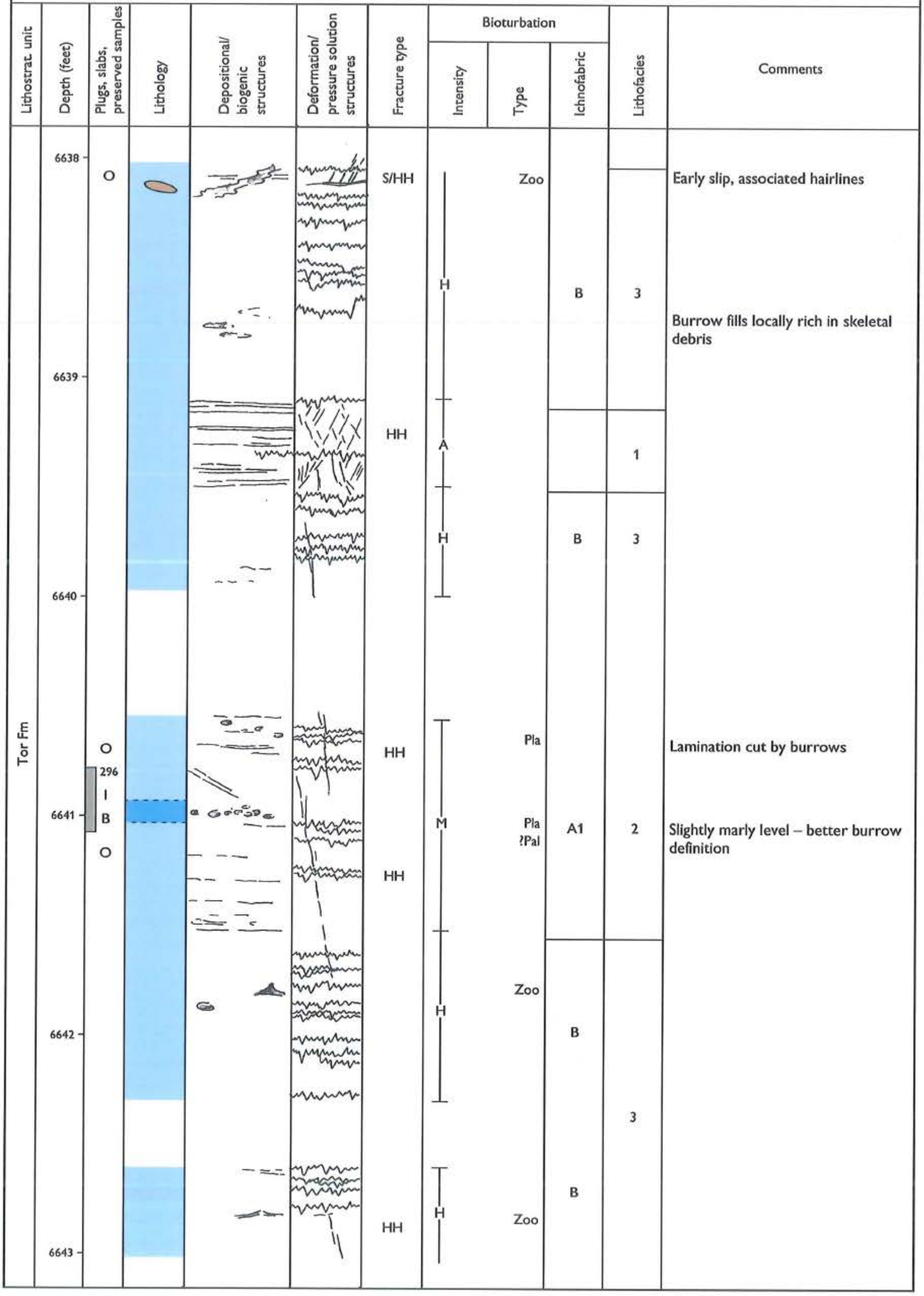
Well-laminated, cut by hairlines

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 7

Scale : c 1:10
Geologist / Logging date : JI, 2/2002

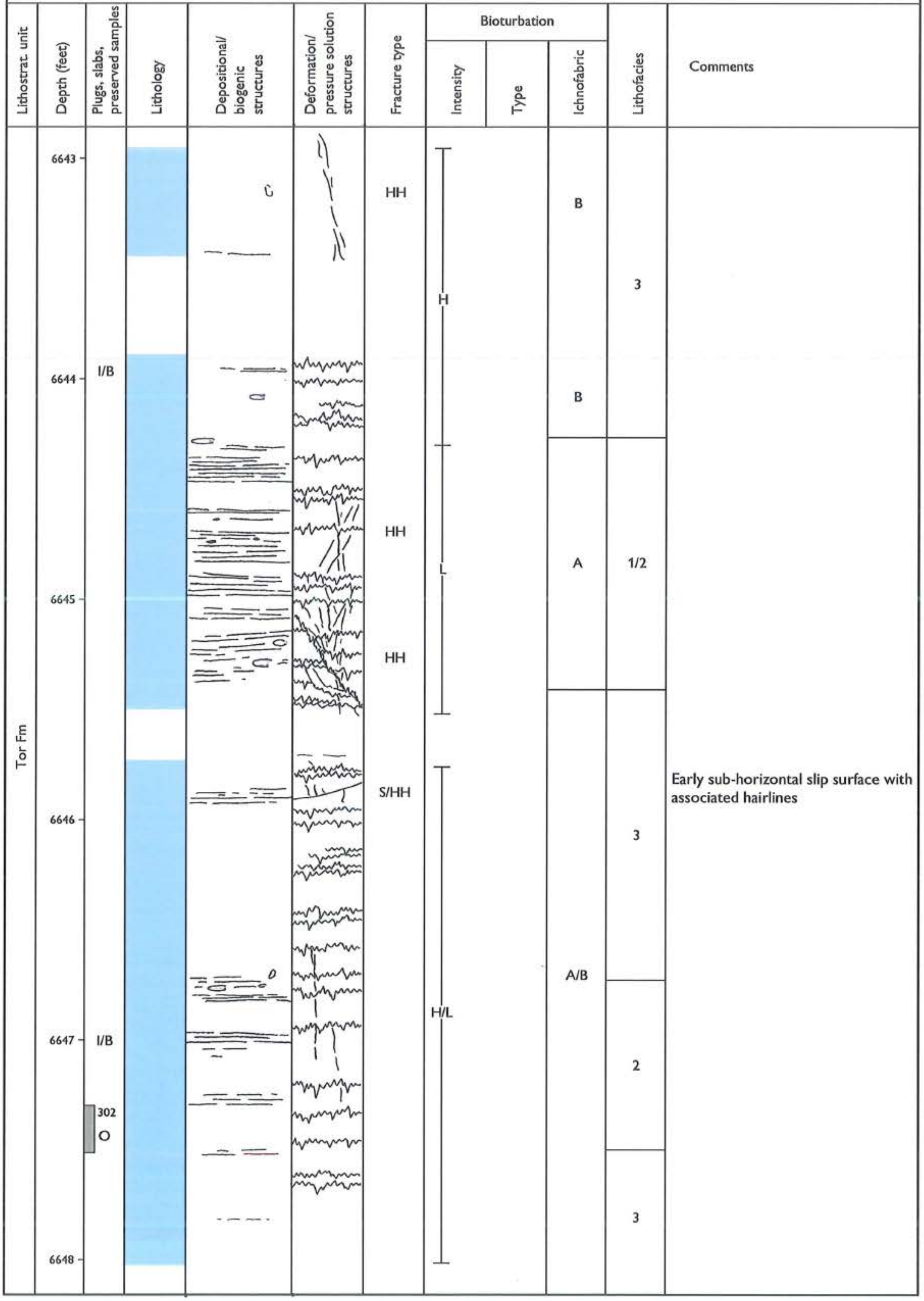


CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 7

Scale : c 1:10
Geologist / Logging date : JI, 2/2002



Early sub-horizontal slip surface with associated hairlines

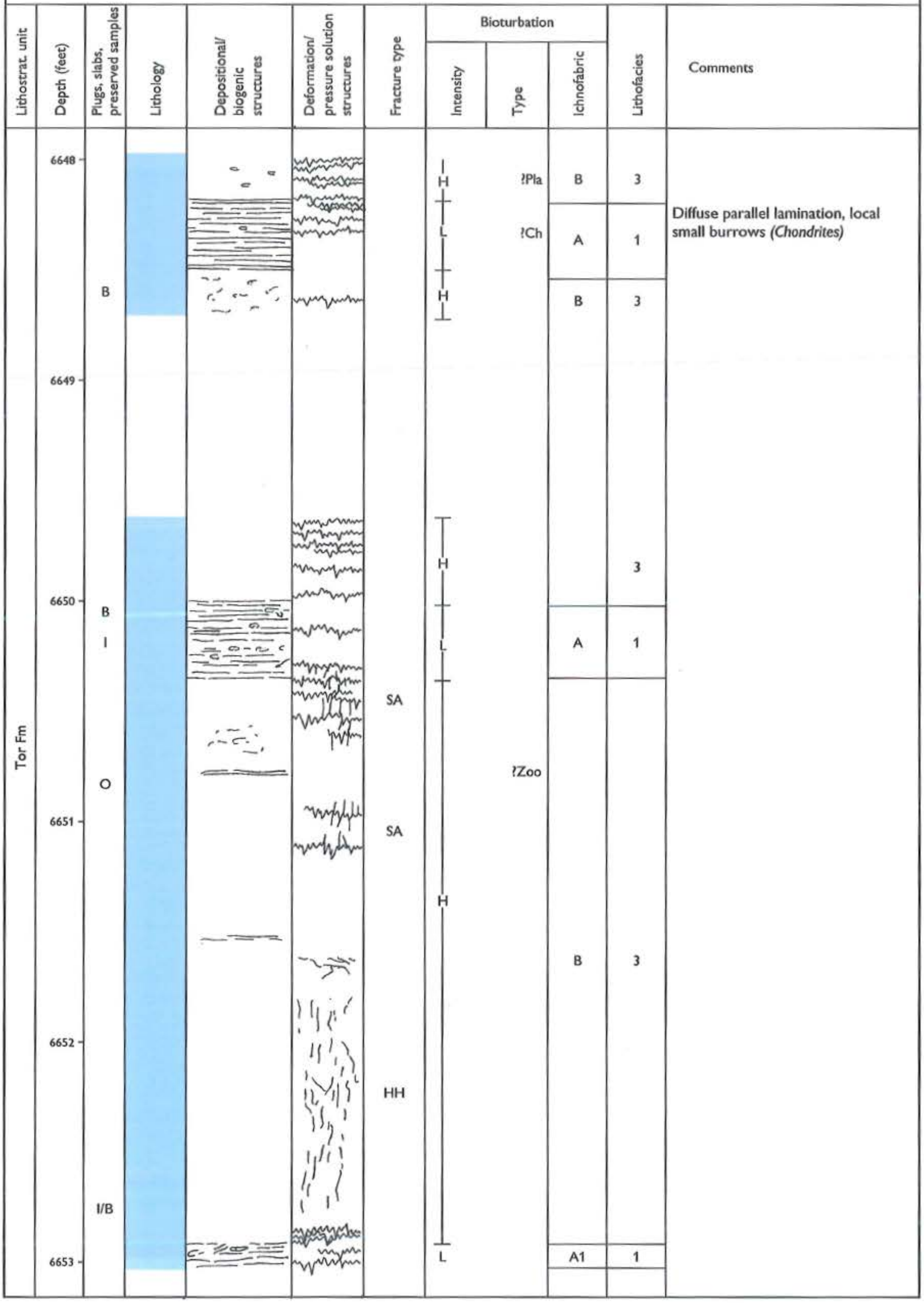
CORE DESCRIPTION

44/45

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 7

Scale : c 1:10
Geologist / Logging date : JI, 2/2002



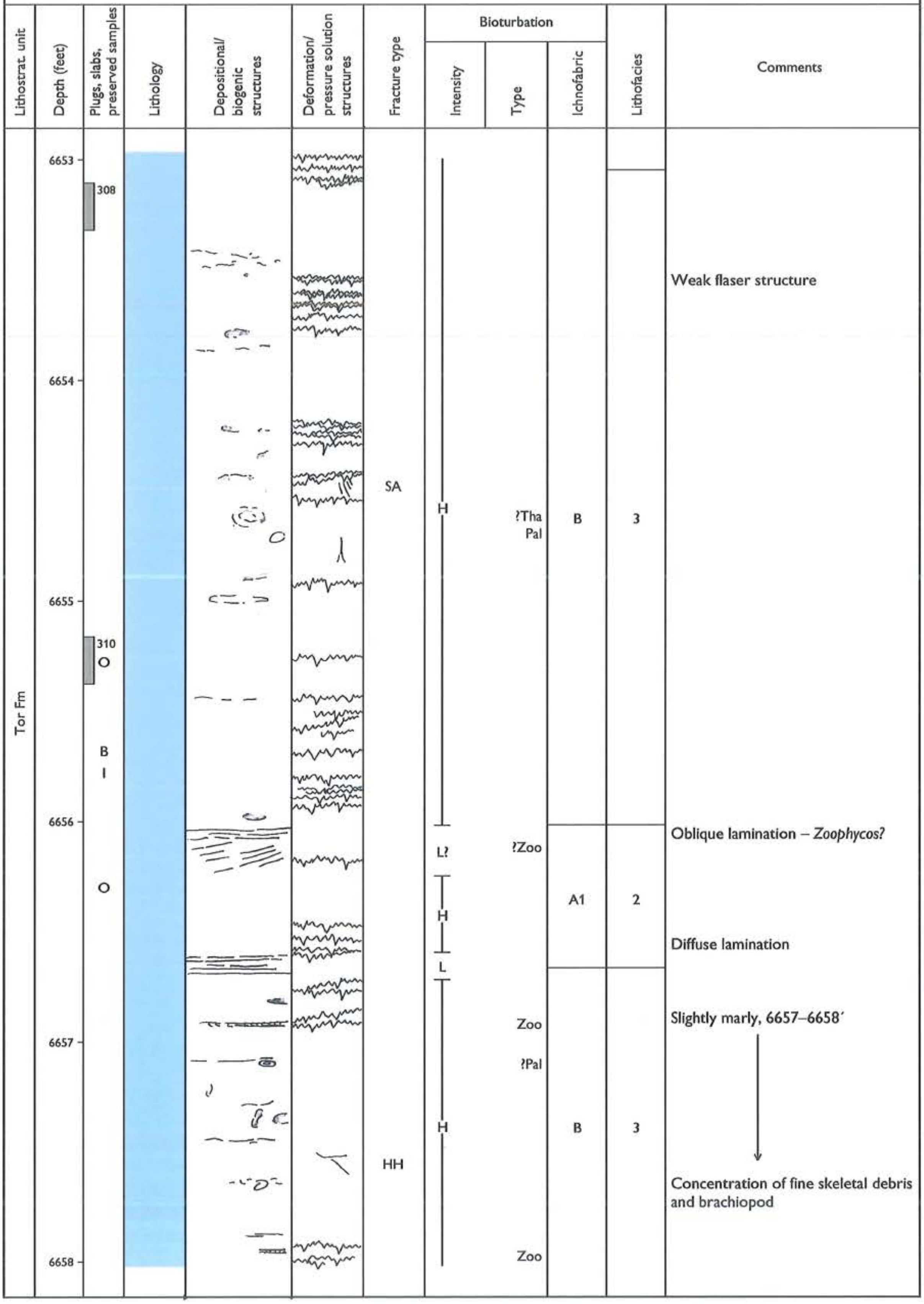
Diffuse parallel lamination, local small burrows *(Chondrites)*

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 7

Scale : c 1:10
Geologist / Logging date : Jl, 2/2002



Weak flaser structure

Oblique lamination – *Zoophycos?*

Diffuse lamination

Slightly marly, 6657–6658′

Concentration of fine skeletal debris and brachiopod

Appendix 2: E-5X core logs

Legend

Lithology

🟦	Chalk
🟦	Mudstone
▨	Wackestone
▨	Packstone/grainstone
🟦	Marly chalk
🟩	Marlstone
🟫	Chert

Fractures etc.

〰	Stylolite
S	Slip/shear plane
HH	Healed hairline fracture
SA	Stylolite-associated fracture
C	Calcite-cemented fracture
O	Open fracture

Bed boundaries

—	Well-defined
- - -	Diffuse bedding trace

Other abbreviations

blk	black
cs	coarse
gnl	granule
gnst	grainstone
gy	grey
m	medium
mlst	marlstone
v cs	very coarse
wkst	wackestone

Plugs etc.

○	Horizontal plug
I	Isotope sample
B	Biostratigraphic sample
▯	Polished slab

Bioturbation

Intensity

A	Absent
L	Low
M	Medium
H	High

Trace fossils

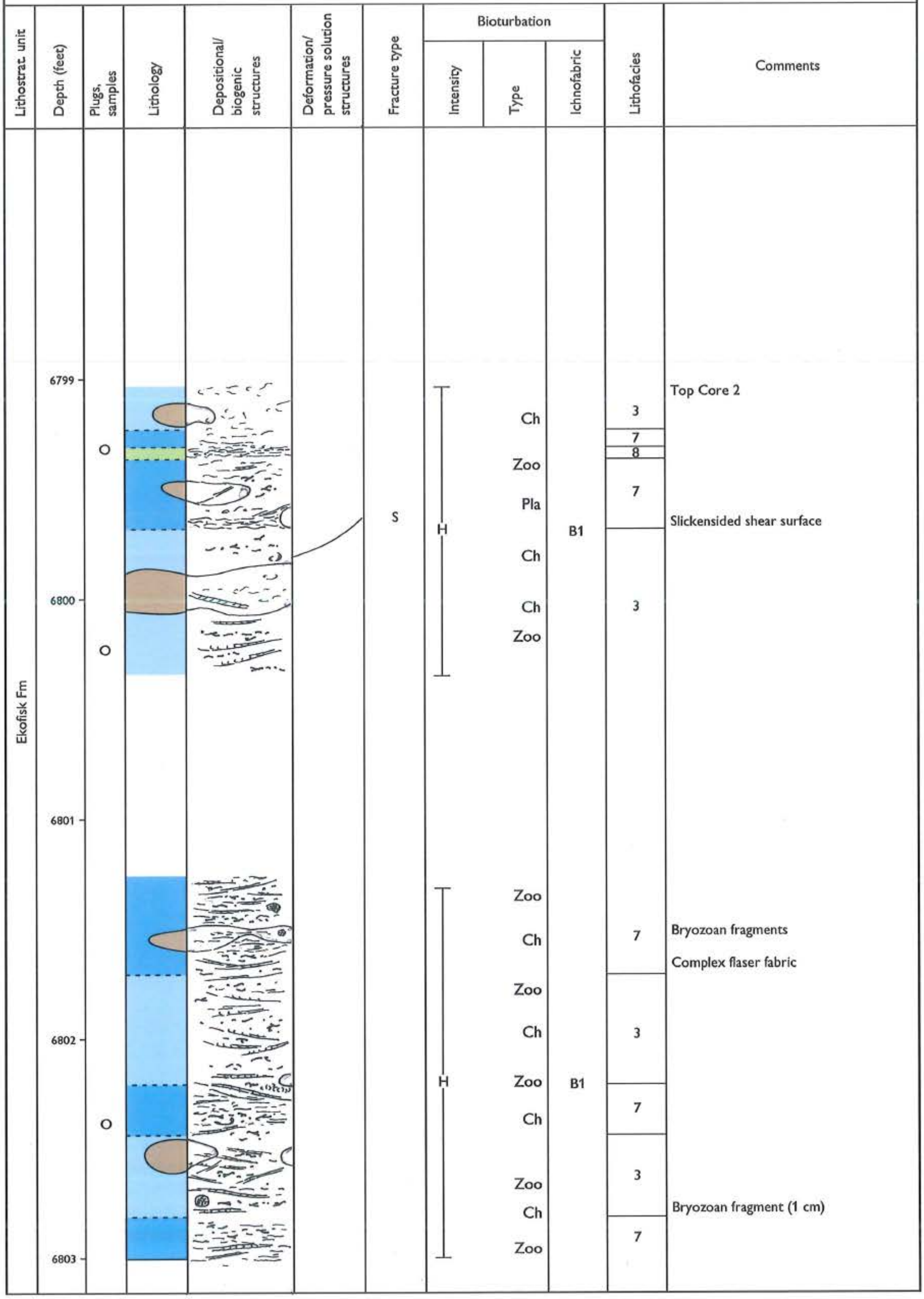
Ch	*Chondrites*
Hel	*Helminthopsis*
Pal	*Palaeophycus*
Pla	*Planolites*
Taen	*Taenidium*
Tei	*Teichichnus*
Tha	*Thalassinoides*
Zoo	*Zoophycos*
?Ast	*Asterosoma*

CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Ekofisk Fm

Well : E-5X
Core : 2

Scale : c 1:10
Geologist / Logging date : Jl, 5/2003

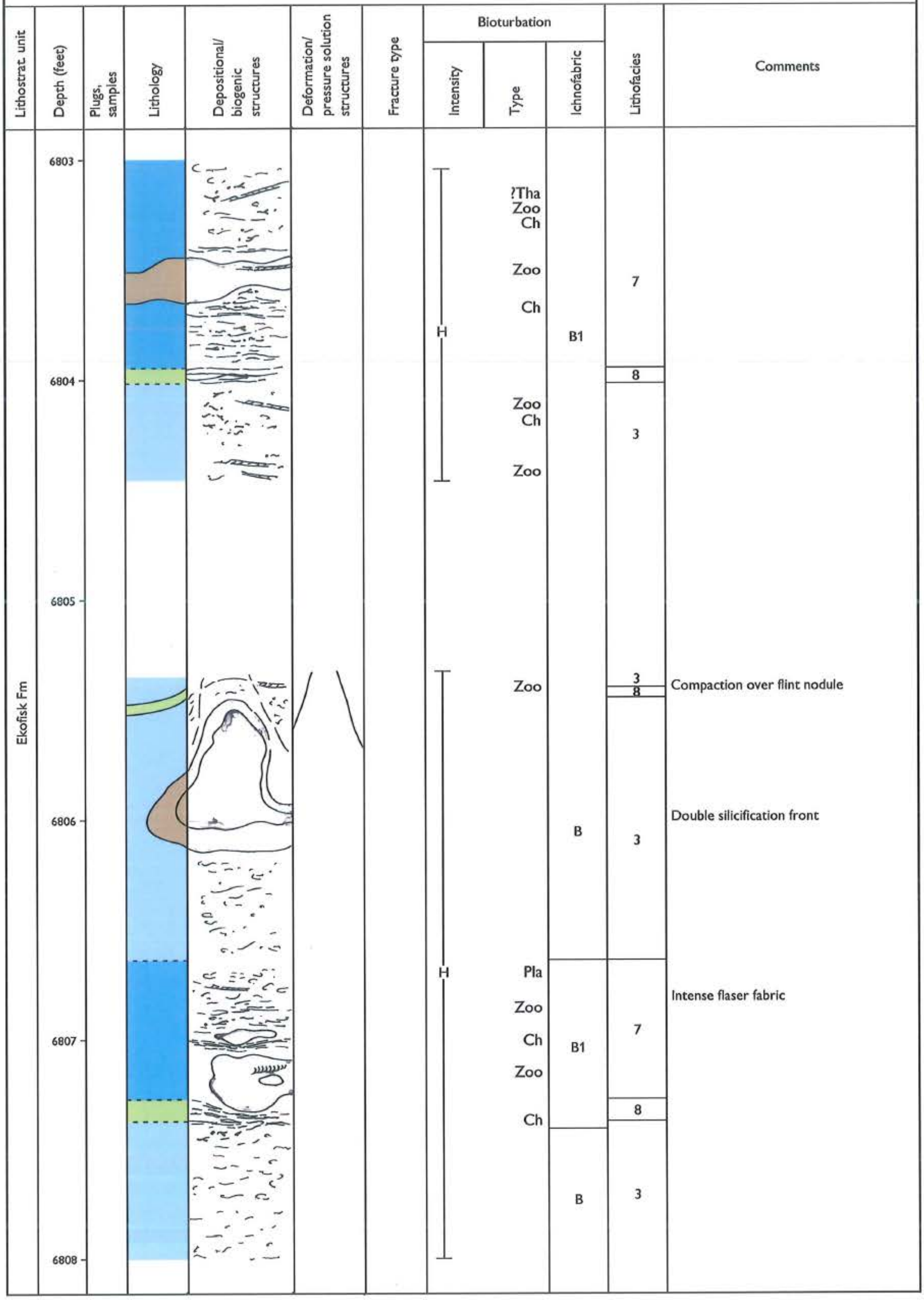


CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Ekofisk Fm

Well : E-5X
Core : 2

Scale : c 1:10
Geologist / Logging date : Jl, 5/2003

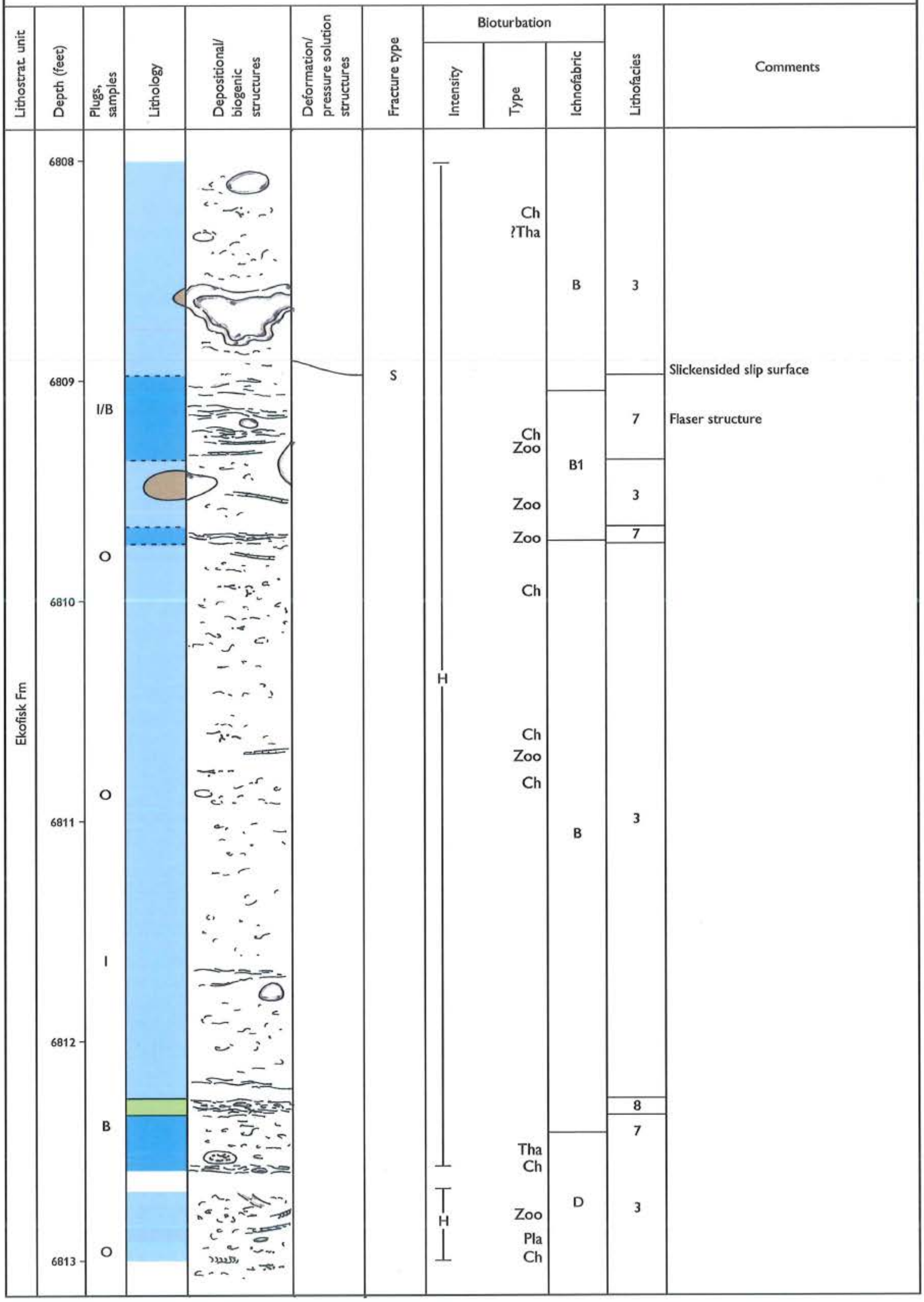


CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Ekofisk Fm

Well : E-5X
Core : 2

Scale : c 1:10
Geologist / Logging date : Jl, 5/2003

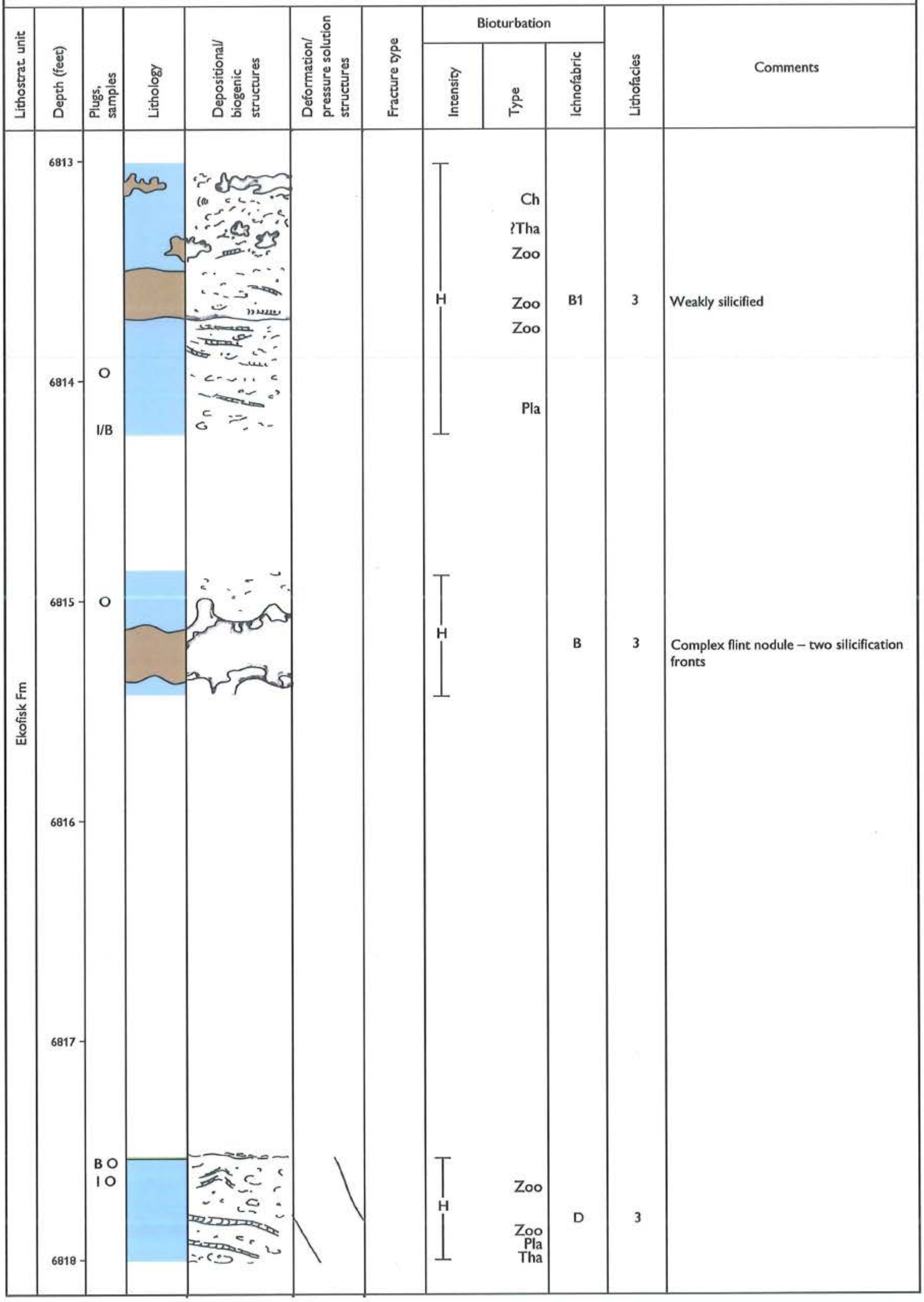


CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Ekofisk Fm

Well : E-5X
Core : 2

Scale : c 1:10
Geologist / Logging date : Jl, 5/2003



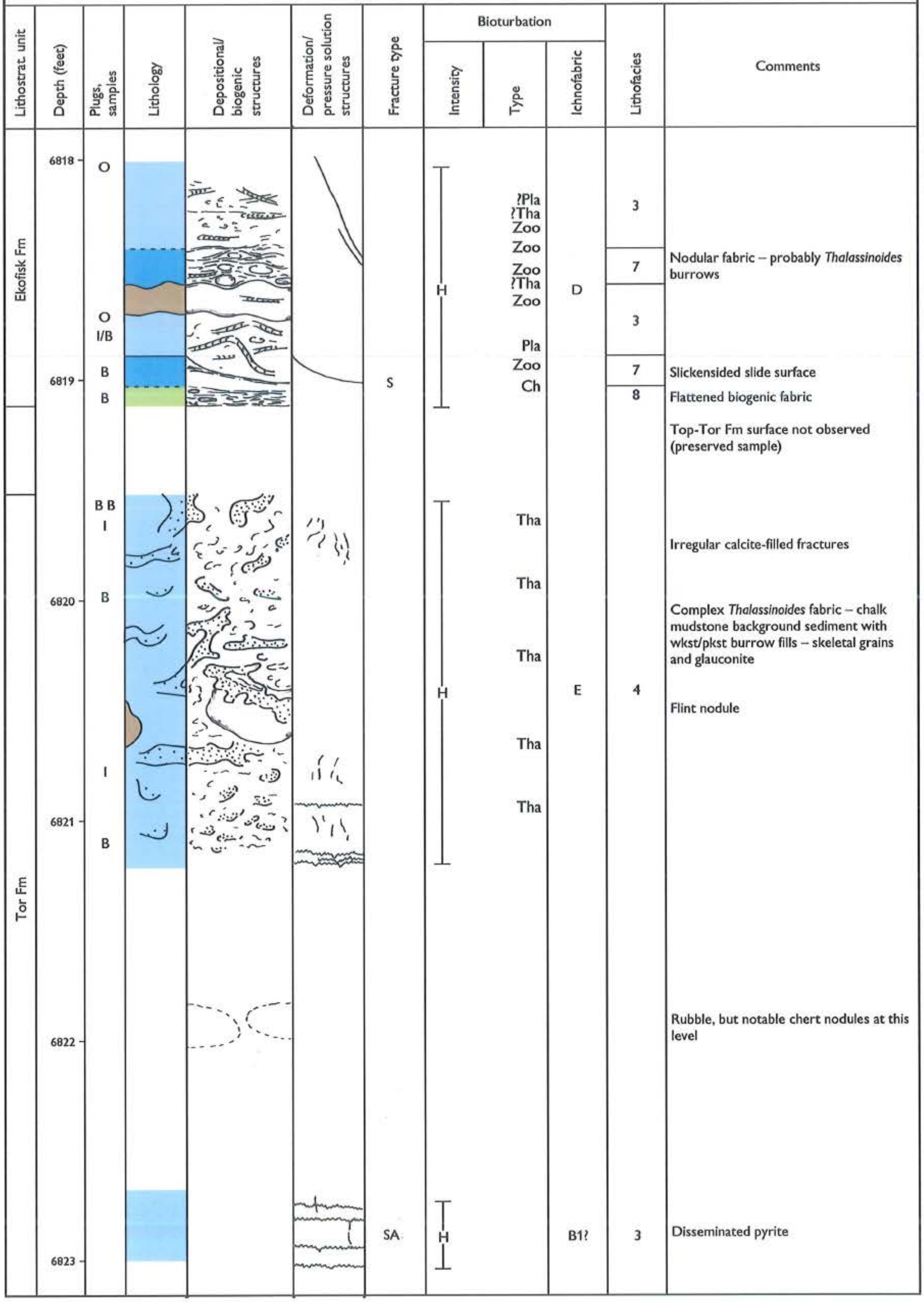
Lithostrat. unit	Depth (feet)	Plugs, samples	Lithology	Depositional/ biogenic structures	Deformation/ pressure solution structures	Fracture type	Bioturbation Intensity	Bioturbation Type	Bioturbation Ichnofabric	Lithofacies	Comments
Ekofisk Fm	6813						H	Ch ?Tha Zoo Zoo Zoo	B1	3	Weakly silicified
	6814	O I/B						Pla			
	6815	O					H		B	3	Complex flint nodule – two silicification fronts
	6816										
	6817	B O I O					H	Zoo Zoo Pla Tha	D	3	
	6818										

CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor/Ekofisk Fms

Well : E-5X
Core : 2

Scale : c 1:10
Geologist / Logging date : Jl, 5/2003



Nodular fabric – probably *Thalassinoides* burrows

Slickensided slide surface

Flattened biogenic fabric

Top-Tor Fm surface not observed (preserved sample)

Irregular calcite-filled fractures

Complex *Thalassinoides* fabric – chalk mudstone background sediment with wkst/pkst burrow fills – skeletal grains and glauconite

Flint nodule

Rubble, but notable chert nodules at this level

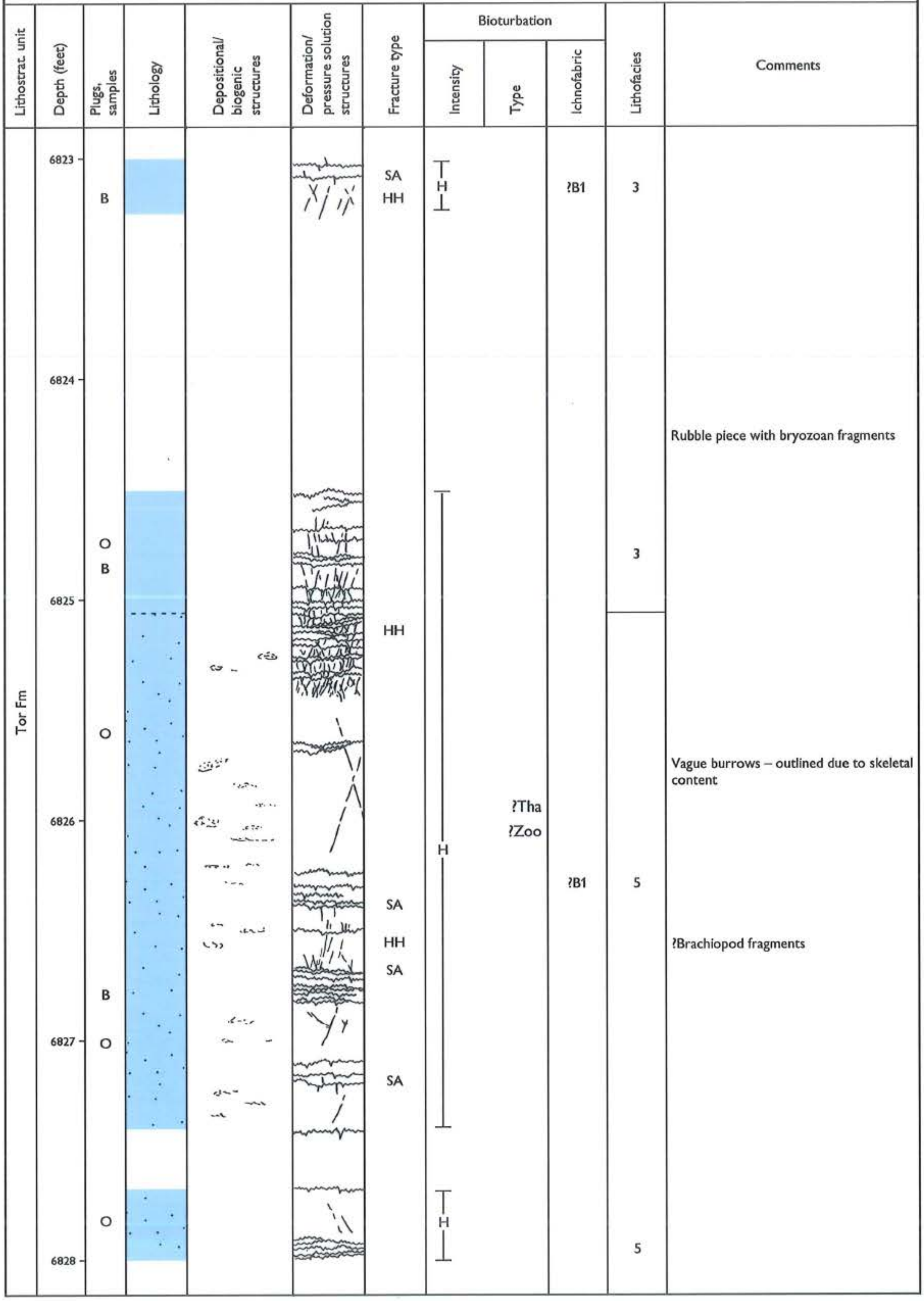
Disseminated pyrite

CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm

Well : E-5X
Core : 2

Scale : c 1:10
Geologist / Logging date : JI, 5/2003



Rubble piece with bryozoan fragments

Vague burrows – outlined due to skeletal content

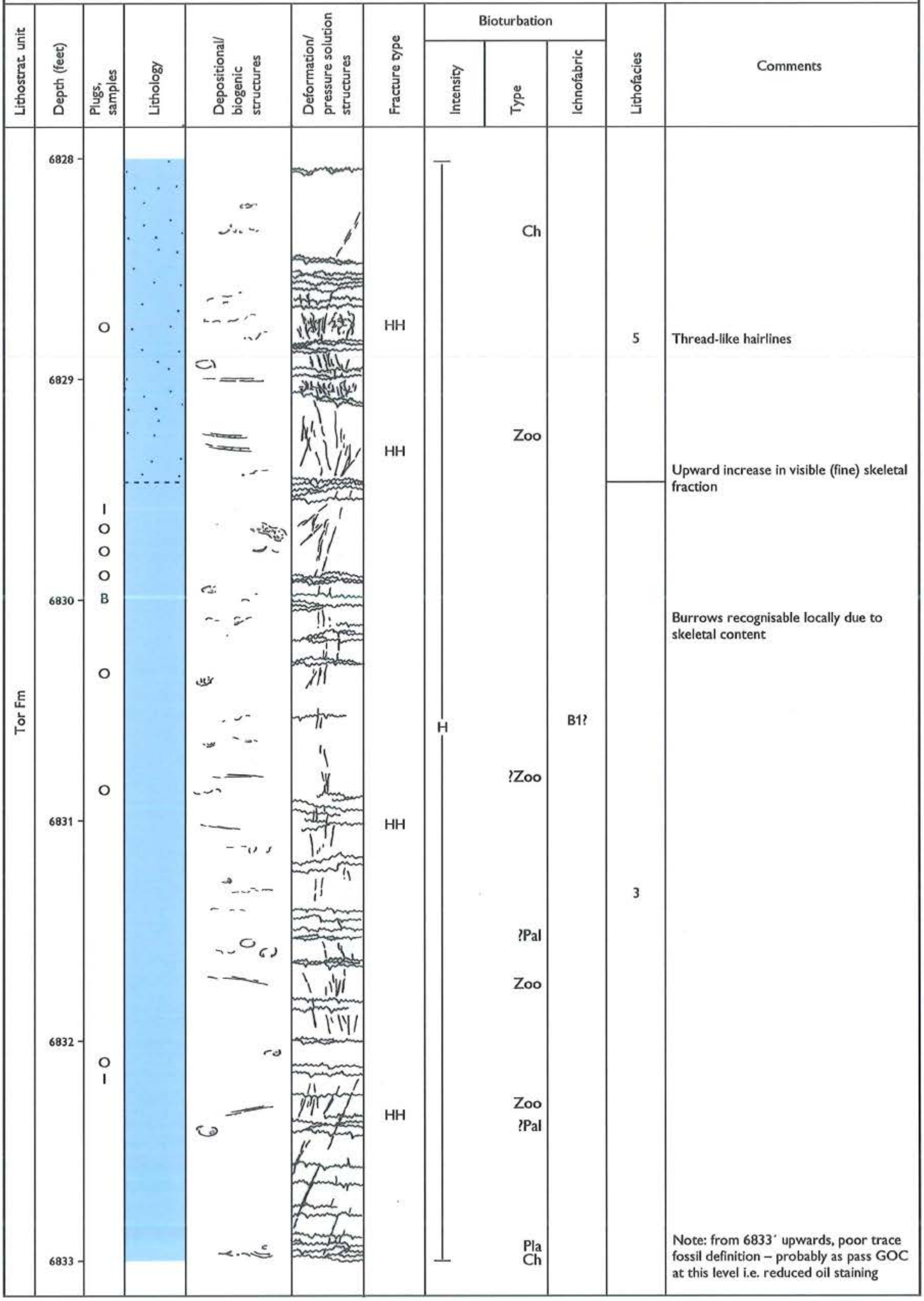
?Brachiopod fragments

CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm

Well : E-5X
Core : 2

Scale : c 1:10
Geologist / Logging date : JI, 5/2003



Thread-like hairlines

Upward increase in visible (fine) skeletal fraction

Burrows recognisable locally due to skeletal content

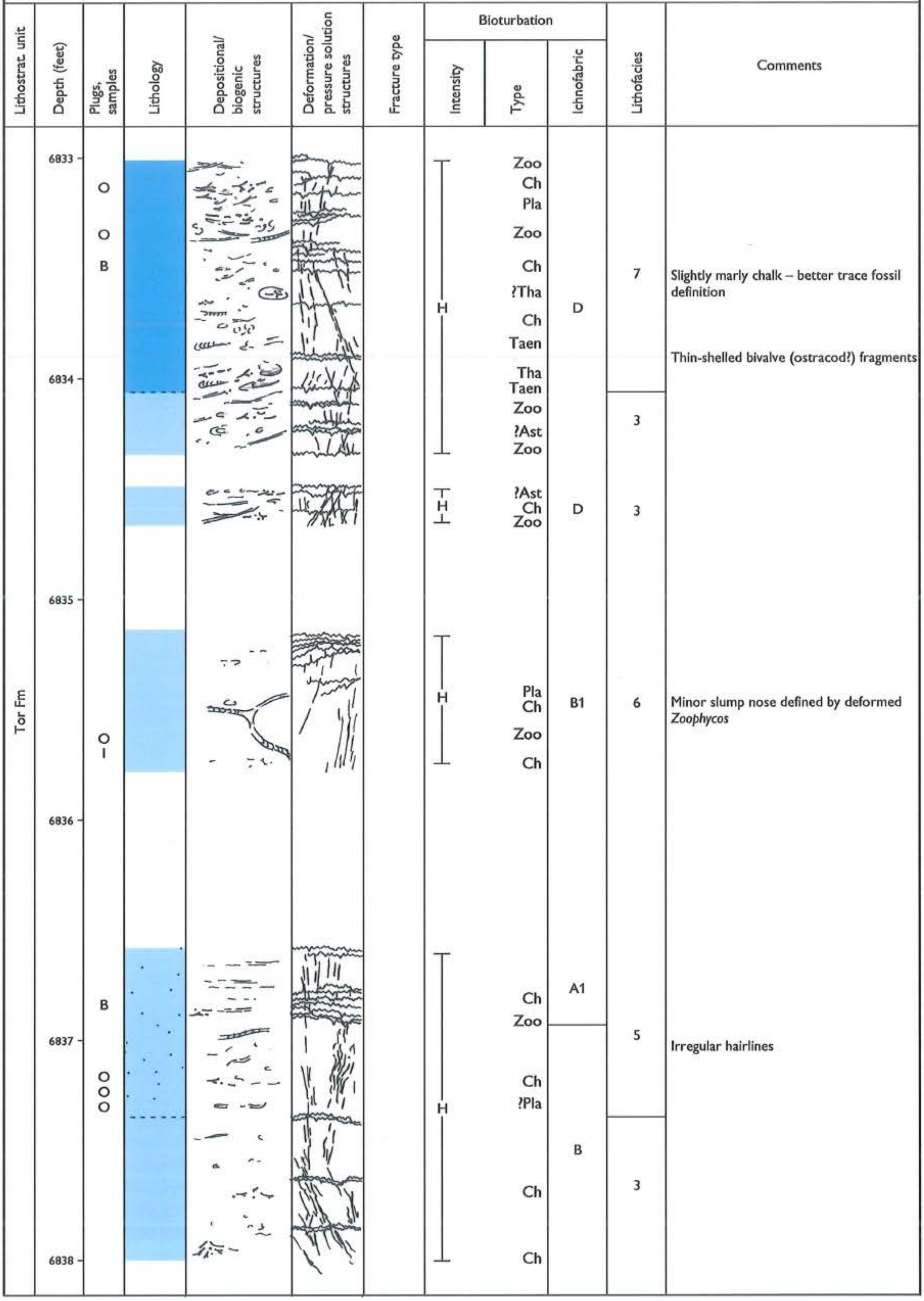
Note: from 6833´ upwards, poor trace fossil definition – probably as pass GOC at this level i.e. reduced oil staining

CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm

Well : E-5X
Core : 2

Scale : c 1:10
Geologist / Logging date : JI, 5/2003



Slightly marly chalk – better trace fossil definition

Thin-shelled bivalve (ostracod?) fragments

Minor slump nose defined by deformed *Zoophycos*

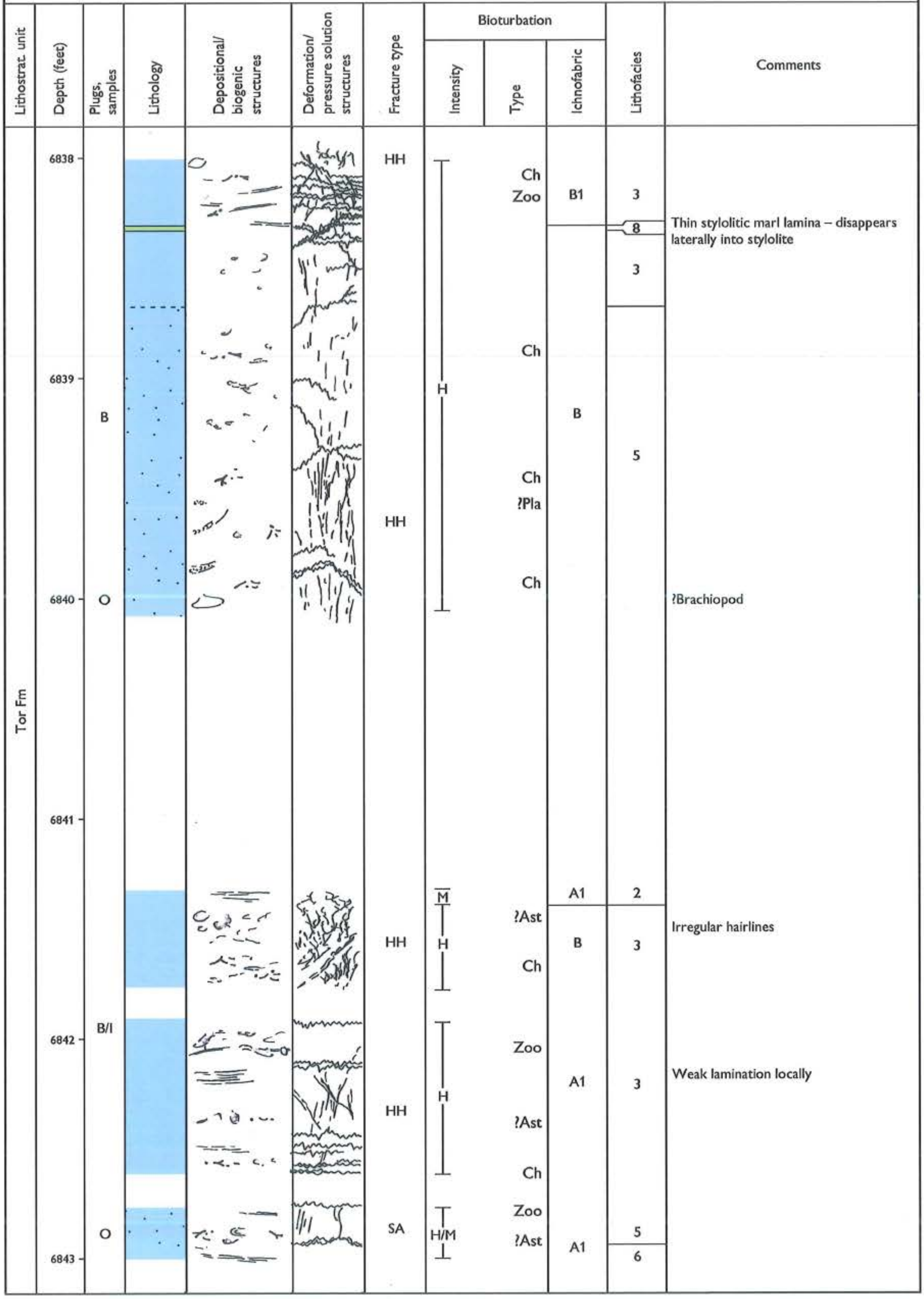
Irregular hairlines

CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm

Well : E-5X
Core : 2

Scale : c 1:10
Geologist / Logging date : Jl, 5/2003



Thin stylolitic marl lamina – disappears laterally into stylolite

?Brachiopod

Irregular hairlines

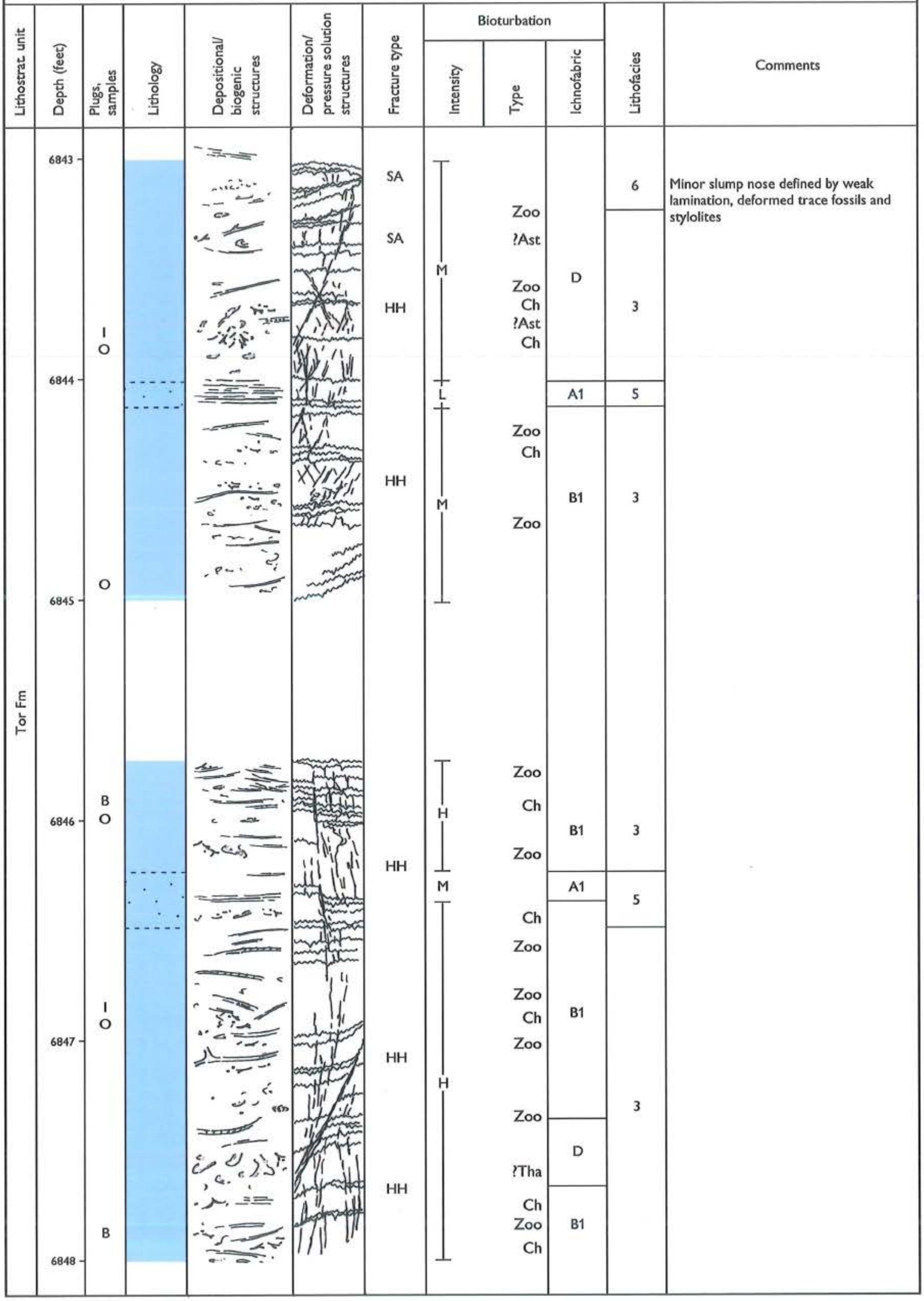
Weak lamination locally

CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm

Well : E-5X
Core : 2

Scale : c 1:10
Geologist / Logging date : JI, 5/2003



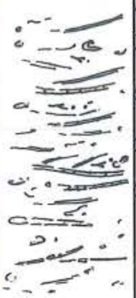
Minor slump nose defined by weak lamination, deformed trace fossils and stylolites

CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm

Well : E-5X
Core : 2

Scale : c 1:10
Geologist / Logging date : JI, 5/2003

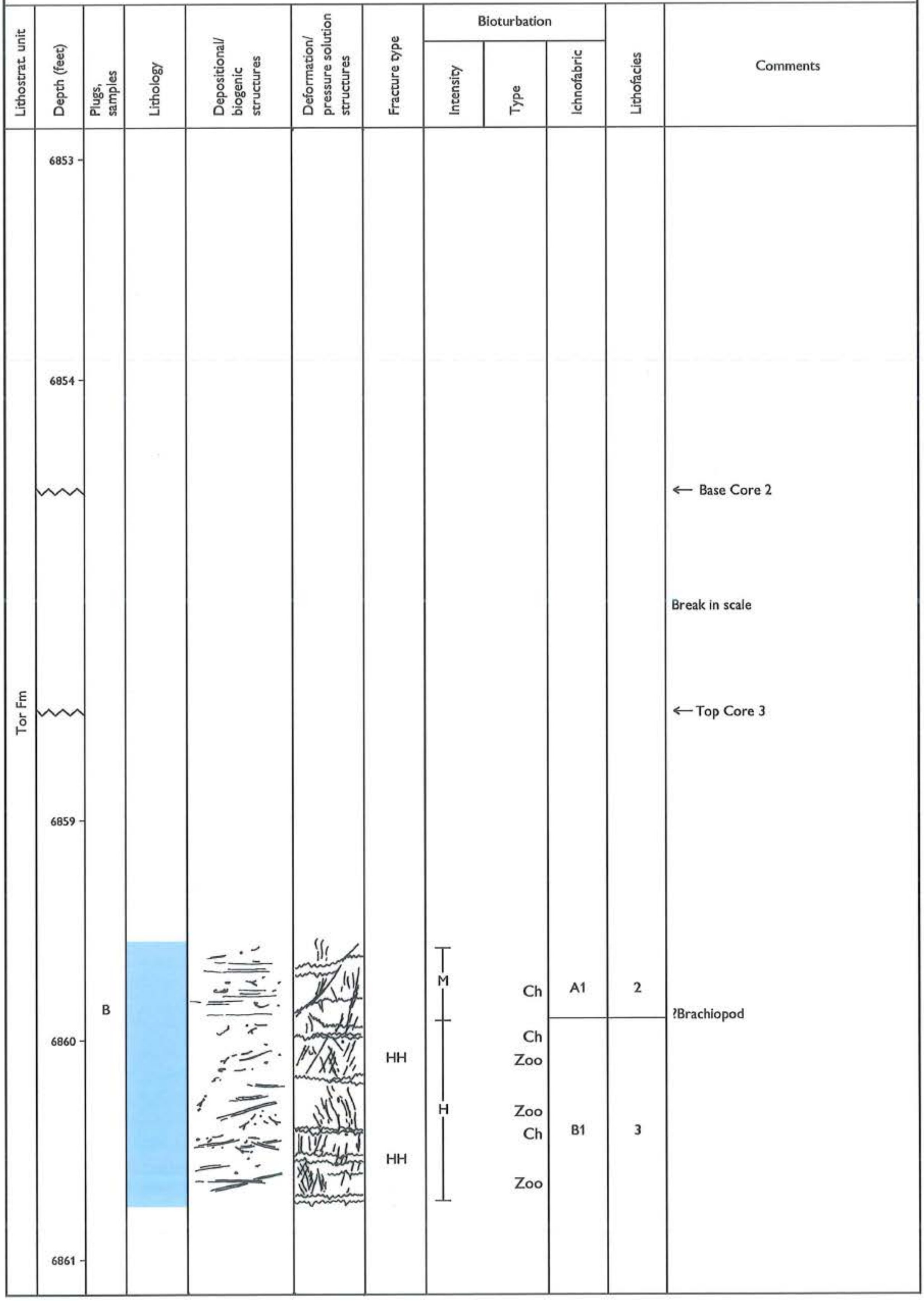
Lithostrat. unit	Depth (feet)	Plugs, samples	Lithology	Depositional/ biogenic structures	Deformation/ pressure solution structures	Fracture type	Bioturbation			Lithofacies	Comments
							Intensity	Type	Ichnofabric		
Tor Fm	6848		🟦			HH	H	Zoo Ch	B1	3	
			🟦			HH HH	H	Zoo ?Ast Zoo Ch Zoo Ch Pla Zoo Ch	D	3	
	6849										
	6850	I									Rubble – few slabbed fragments (c. 6850′) show wkst fabric and well laminated, occasional burrows
	6851										
	6852										
	6853										

CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm

Well : E-5X
Core :3/ 2

Scale : c 1:10
Geologist / Logging date : JI, 5/2003

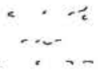


CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm

Well : E-5X
Core : 3

Scale : c 1:10
Geologist / Logging date : Jl, 4/2003

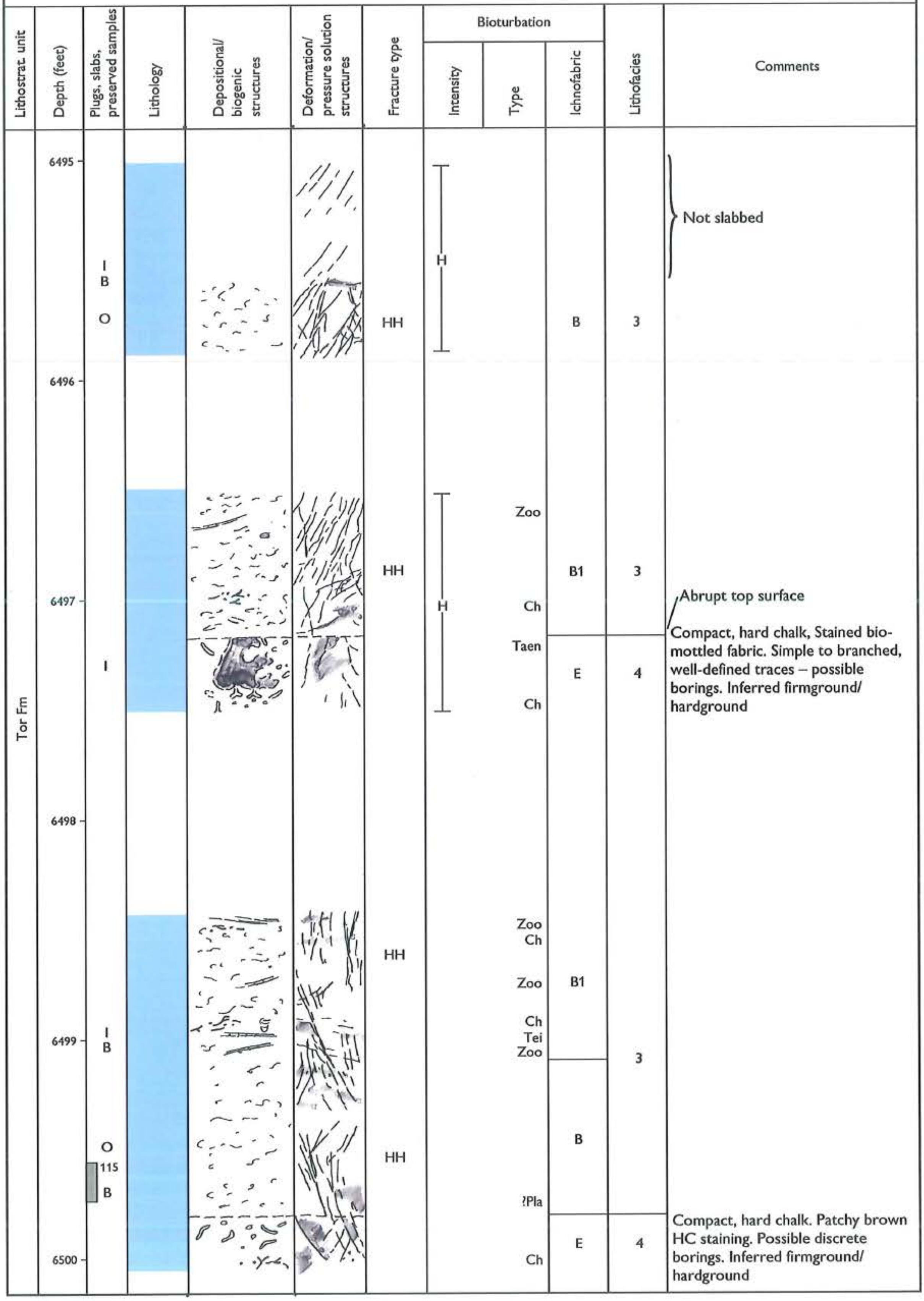
Lithostrat. unit	Depth (feet)	Plugs, samples	Lithology	Depositional/ biogenic structures	Deformation/ pressure solution structures	Fracture type	Bioturbation Intensity	Bioturbation Type	Ichnofabric	Lithofacies	Comments
Tor Fm	6861										
	6862	I									
											No salvagable section – rubble; samples taken for biostrat./isotopes at approx levels
	6863										
		B									
	6864										
		I	🟦			HH	H		?B	3	
	6865										
	6866										

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 5

Scale : c 1:10
Geologist / Logging date : Jl, 3/2002



Not slabbed

Abrupt top surface

Compact, hard chalk, Stained bio-mottled fabric. Simple to branched, well-defined traces – possible borings. Inferred firmground/ hardground

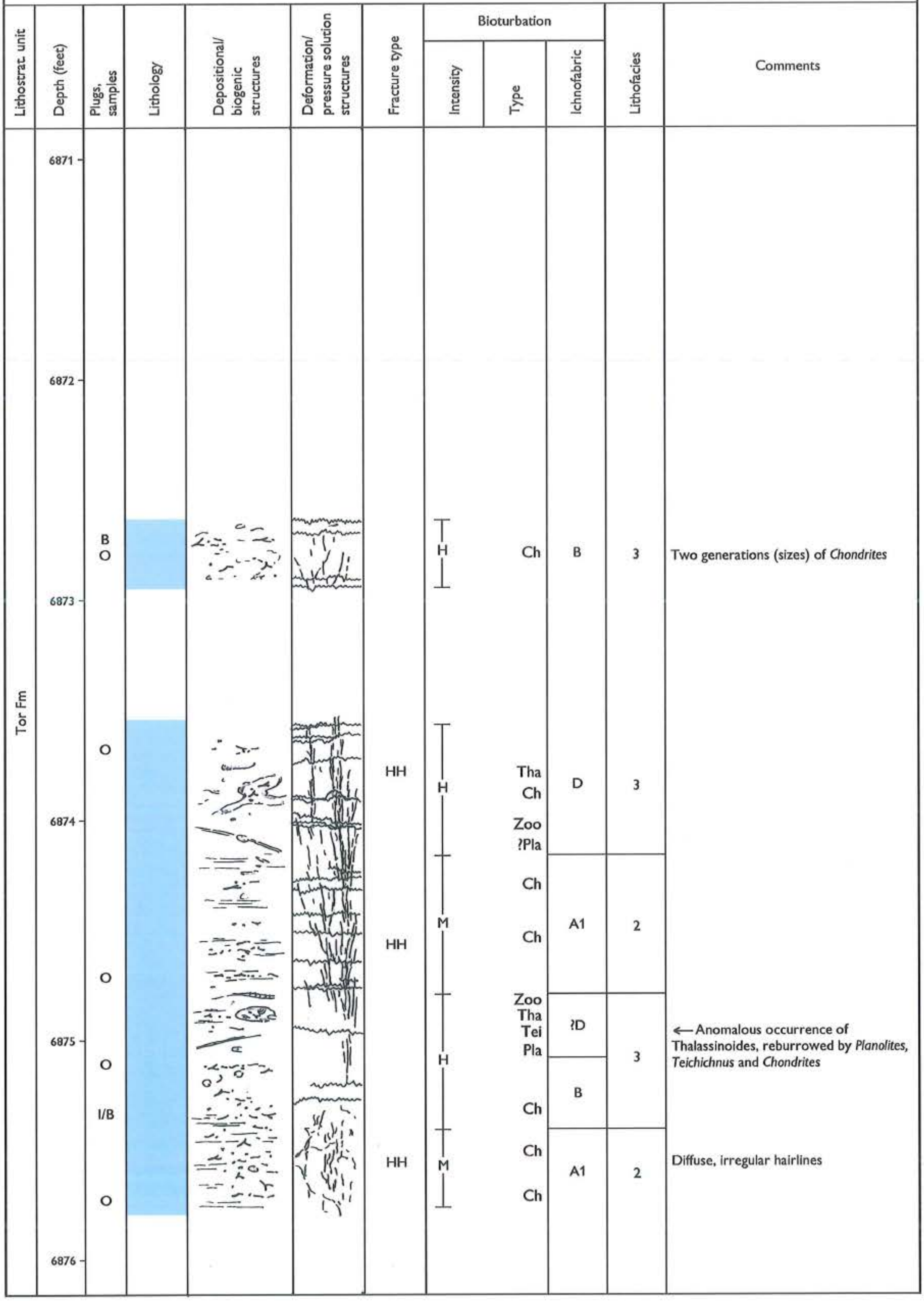
Compact, hard chalk. Patchy brown HC staining. Possible discrete borings. Inferred firmground/ hardground

CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm

Well : E-5X
Core : 3

Scale : c 1:10
Geologist / Logging date : Jl, 4/2003



Two generations (sizes) of *Chondrites*

← Anomalous occurrence of Thalassinoides, reburrowed by *Planolites*, *Teichichnus* and *Chondrites*

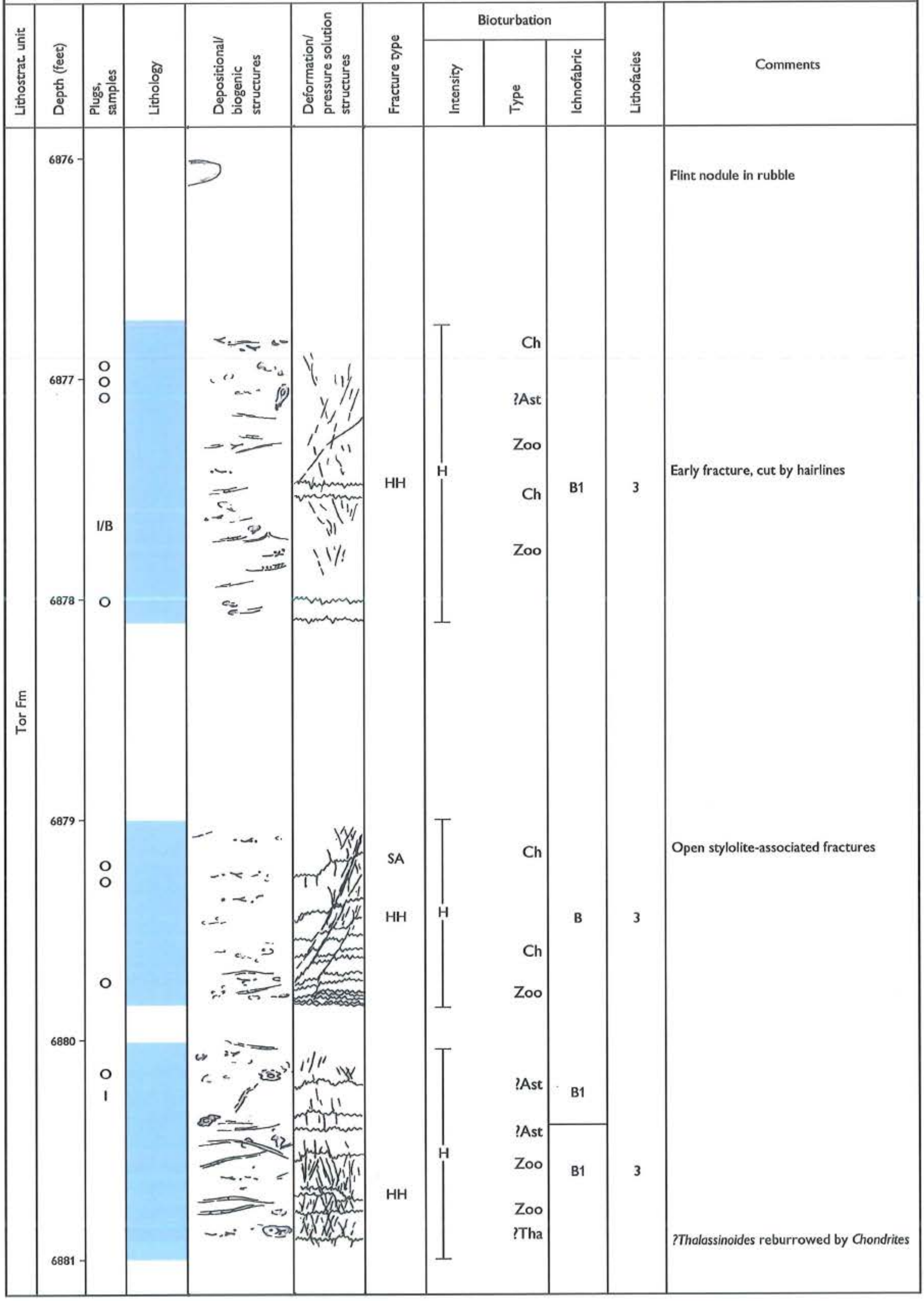
Diffuse, irregular hairlines

CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm

Well : E-5X
Core : 3

Scale : c 1:10
Geologist / Logging date : JI, 4/2003



Flint nodule in rubble

Early fracture, cut by hairlines

Open stylolite-associated fractures

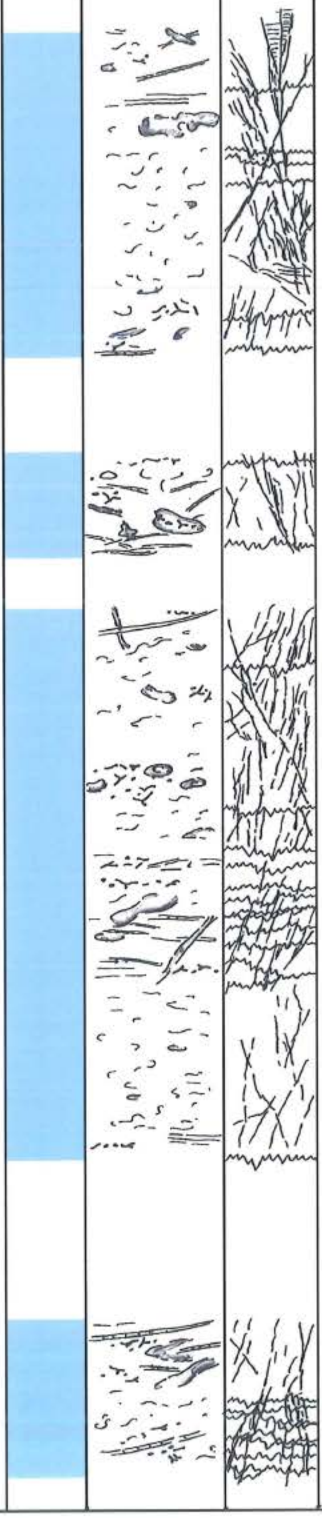
?Thalassinoides reburrowed by *Chondrites*

CORE DESCRIPTION

Field / Area : Dan
Lithostrat. unit : Tor Fm

Well : M-10X
Core : 5

Scale : c 1:10
Geologist / Logging date : Jl, 3/2002



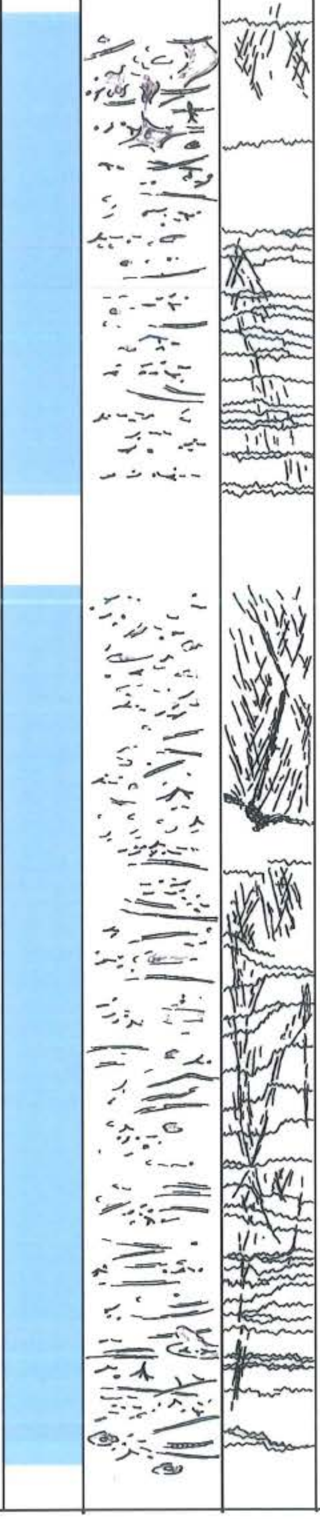
Lithostrat. unit	Depth (feet)	Plugs, slabs, preserved samples	Lithology	Depositional/ biogenic structures	Deformation/ pressure solution structures	Fracture type	Bioturbation Intensity	Bioturbation Type	Ichnofabric	Lithofacies	Comments
Tor Fm	6510 6511	I				HH	H	Ch Zoo ?Tha Ch ?Pla Zoo	B1	3	Dilation fractures between hairlines ?Tha may be artefacts (stain)
		B				HH	H	Ch Pal Zoo Tha/Ch Zoo	D		*Chondrites* reburrowing *?Thalassinoides*
	6512					HH	H	Zoo Ch Ch Ch ?Tha	D	3	
	6513							Ch Zoo ?Tha Zoo	A1	2	
	6514	I 173 O				HH			B	3	
	6515	B				HH	H	Zoo Ch ?Tha Ch Zoo	D	3	

CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm

Well : E-5X
Core : 3

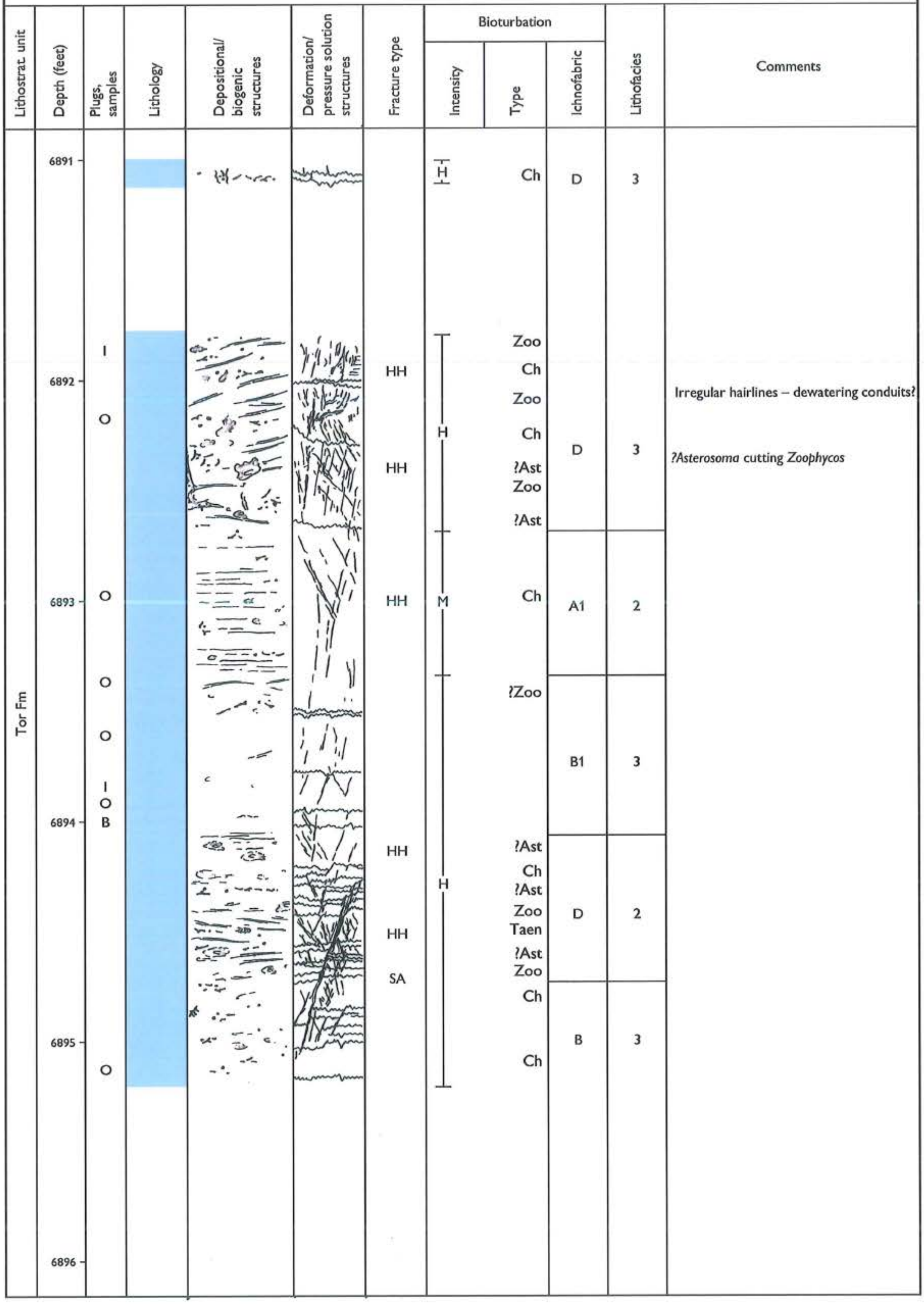
Scale : c 1:10
Geologist / Logging date : Jl, 4/2003



Lithostrat. unit	Depth (feet)	Plugs, samples	Lithology	Depositional/ biogenic structures	Deformation/ pressure solution structures	Fracture type	Bioturbation			Lithofacies	Comments
							Intensity	Type	Ichnofabric		
	6886					HH		Zoo			
								?Tha	D		
		I						Zoo			
								Ch			
								Zoo			
		O						Ch			
							H	Zoo		3	
		O									
	6887					HH		Ch	B1		
		O									
		B						Zoo			
		O						Ch			
	6888										
Tor Fm		O				HH		Zoo			
								Ch			Horizontal slip planes
								Zoo			
	6889										
								Zoo	B1	3	
		B						Ch			
						HH	H				
								Zoo			
	6890							Zoo			
						HH		Zoo			
								Zoo			
								?Tha			*?Thalassinoides* reburrowed by *Chondrites*
		B						Ch	D		
								Zoo			
	6891							?Ast			

CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm
Well : E-5X
Core : 3
Scale : c 1:10
Geologist / Logging date : Jl, 4/2003



Irregular hairlines – dewatering conduits?

?Asterosoma cutting *Zoophycos*

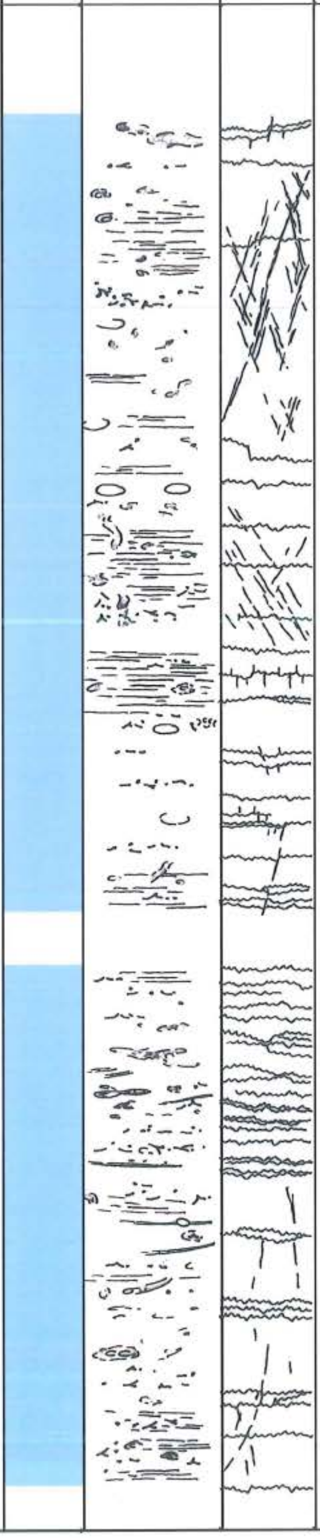
CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm

Well : E-5X
Core : 3

Scale : c 1:10
Geologist / Logging date : JI, 4/2003

Columns: Lithostrat. unit | Depth (feet) | Plugs, samples | Lithology | Depositional/ biogenic structures | Deformation/ pressure solution structures | Fracture type | Bioturbation: Intensity, Type, Ichnofabric | Lithofacies | Comments



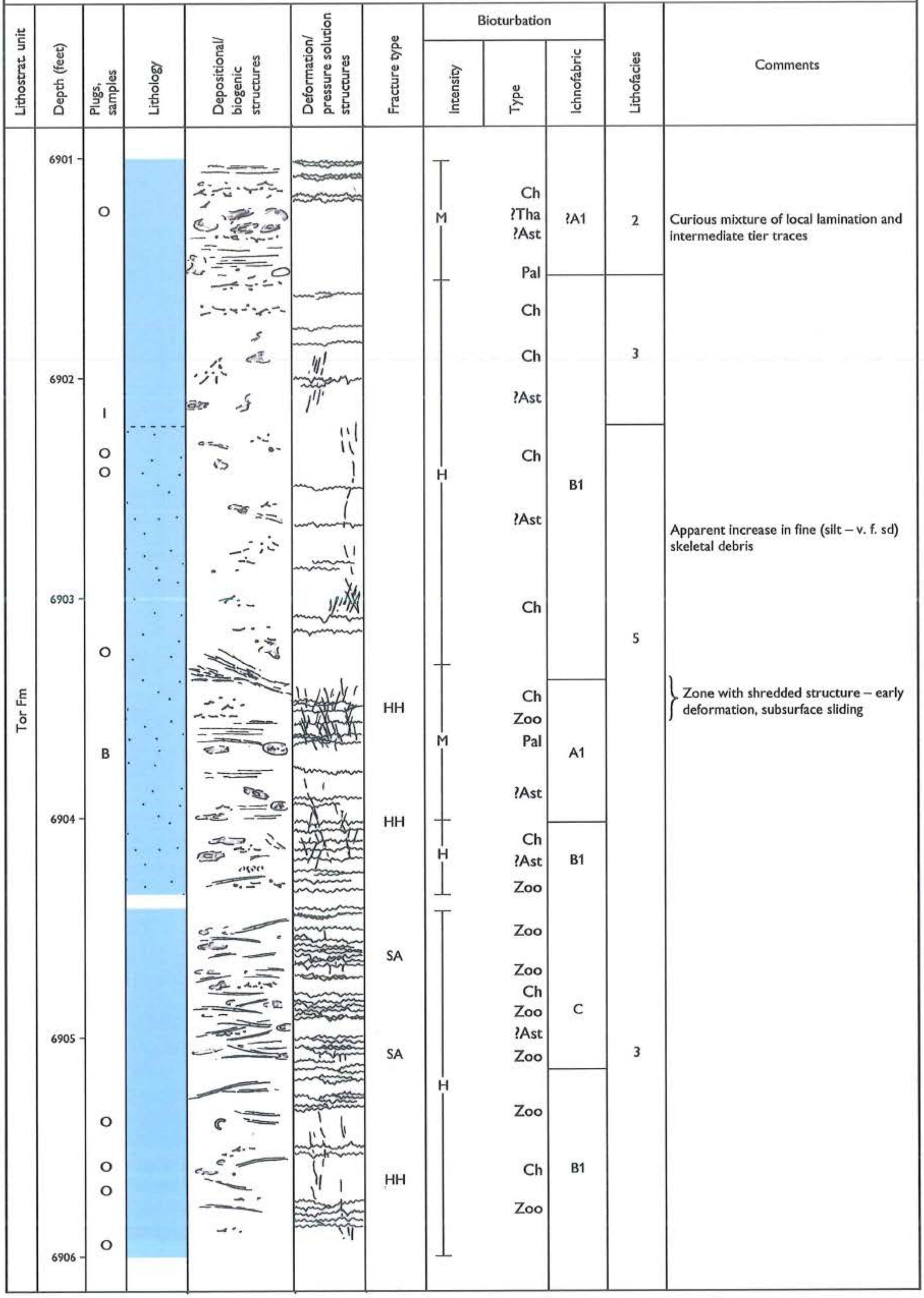
Lithostrat. unit	Depth (feet)	Plugs, samples	Fracture type	Bioturbation Intensity	Bioturbation Type	Bioturbation Ichnofabric	Lithofacies	Comments
Tor Fm	6896							
			SA					
					Ch ?Ast	B1	3	
		O I				A1	2	
					Ch			Conjugate hairlines
			HH		Pal	B1	3	
	6897							
		O			Pal			
					Ch			
					Pal			
				H				
						A1	2	
					Ch			
		B	HH					
	6898				Ch			
			SA					
		O			?Ast			
					Pal			Horizontal straight *Palaeophycus* (20 x 5 mm in XS) on bedding surface; burrow lined by thin dark ?organic sheath
			SA					
		O				B1	3	
					Ch			
					Ch	A1	2	
	6899							
						A1	2	
					Ch			
					Zoo ?Ast Ch	B1	3	
					Ch Zoo			
	6900	O						
				H	Zoo	A1	2	
		O			Ch			
					?Ast			
		O I			?Ast	B1	3	
			HH		Ch			
		B			?Ast			
		O			Ch	A1	2	
	6901							

CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm

Well : E-5X
Core : 3

Scale : c 1:10
Geologist / Logging date : JI, 4/2003



Curious mixture of local lamination and intermediate tier traces

Apparent increase in fine (silt – v. f. sd) skeletal debris

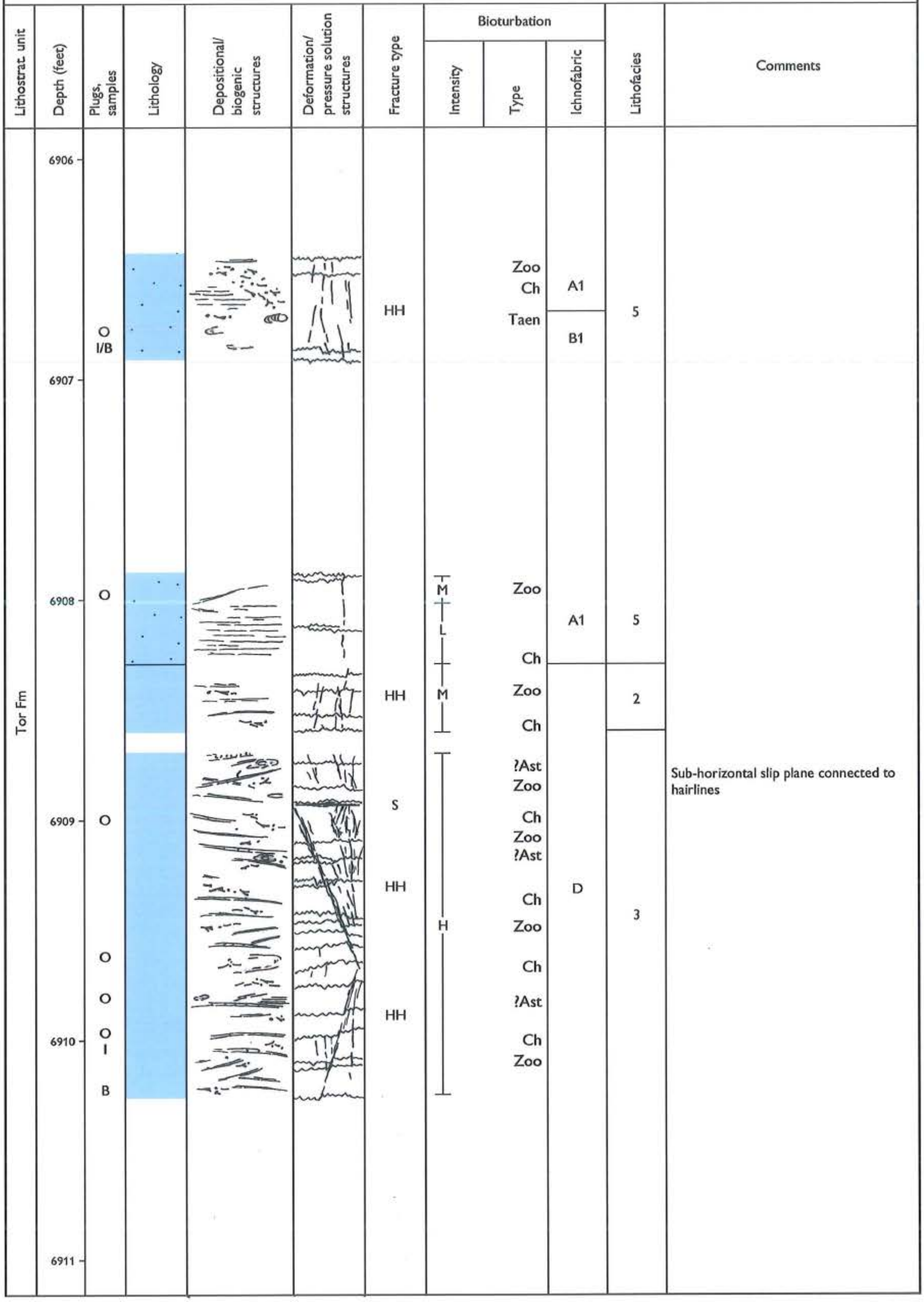
} Zone with shredded structure – early deformation, subsurface sliding

CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm

Well : E-5X
Core : 3

Scale : c 1:10
Geologist / Logging date : Jl, 4/2003



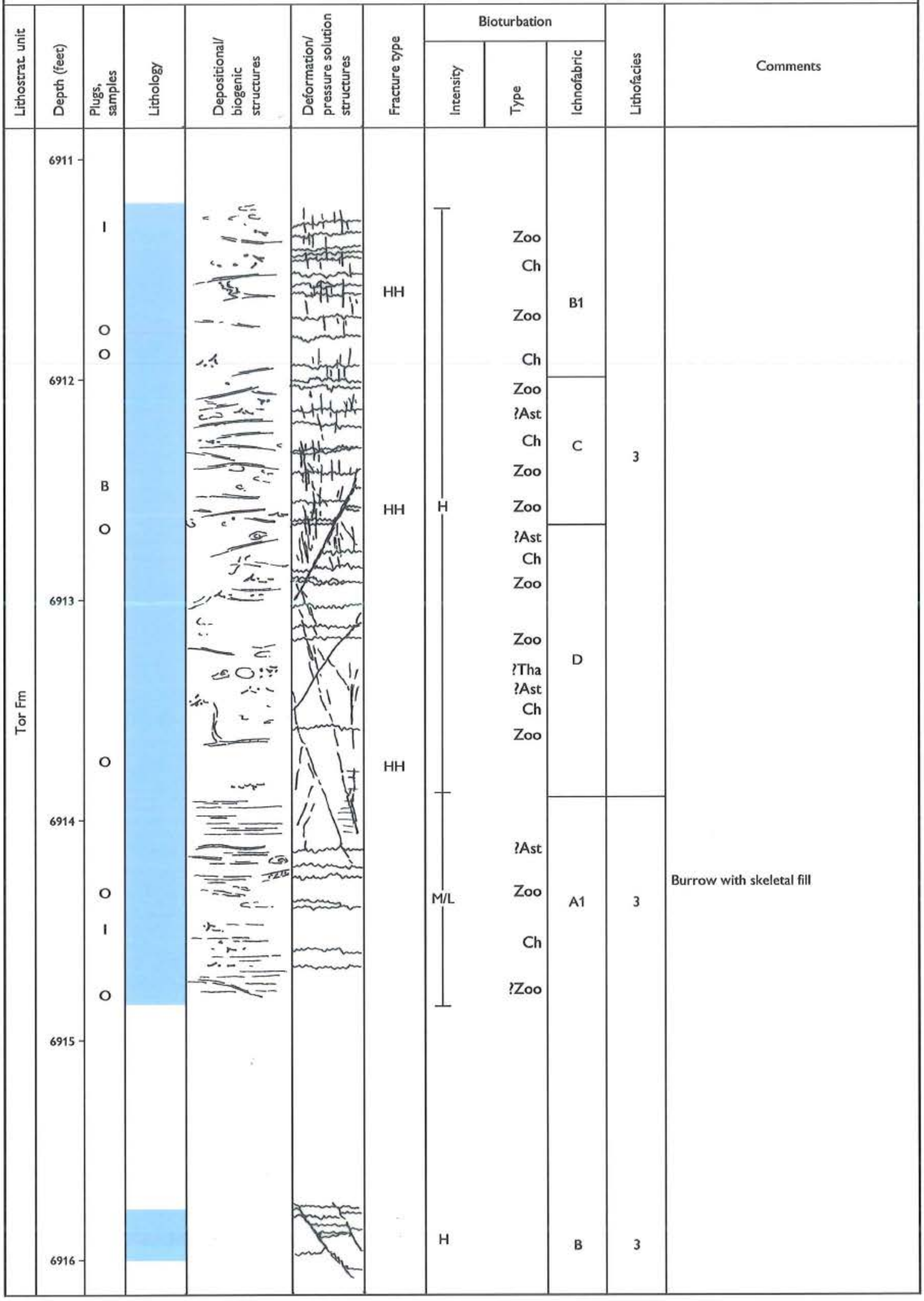
Sub-horizontal slip plane connected to hairlines

CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm

Well : E-5X
Core : 3

Scale : c 1:10
Geologist / Logging date : JI, 4/2003

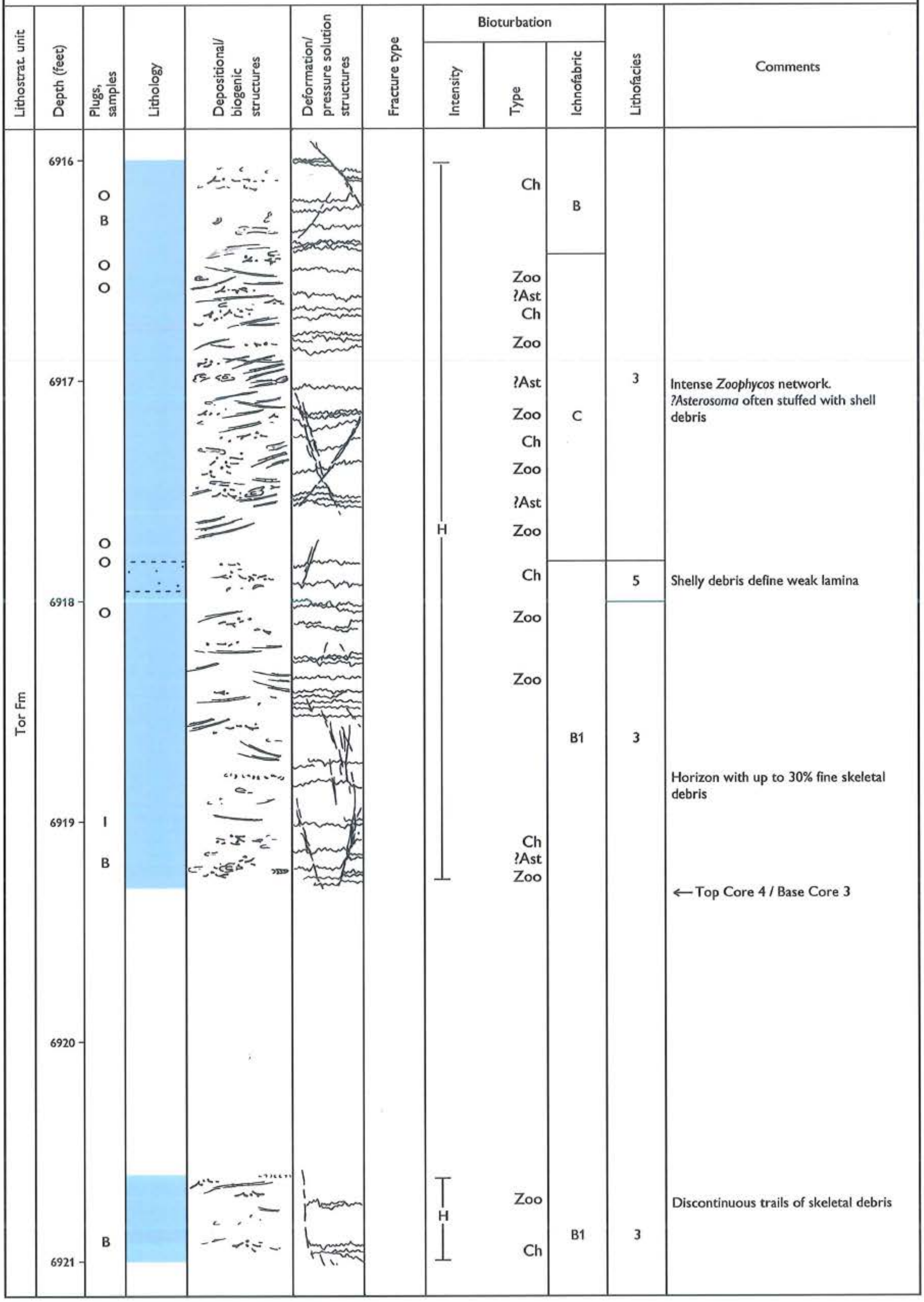


CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm

Well : E-5X
Core : 4/3

Scale : c 1:10
Geologist / Logging date : Jl, 4/2003



Intense *Zoophycos* network. *?Asterosoma* often stuffed with shell debris

Shelly debris define weak lamina

Horizon with up to 30% fine skeletal debris

←Top Core 4 / Base Core 3

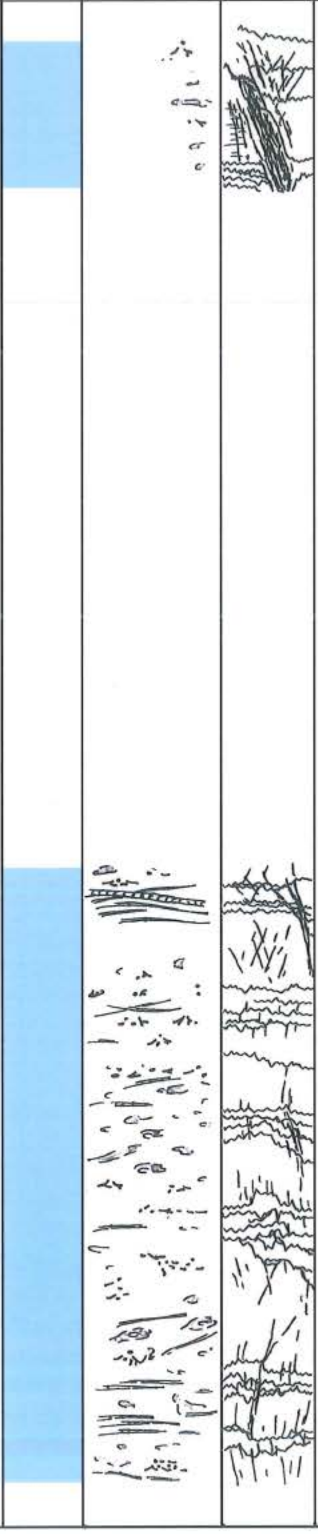
Discontinuous trails of skeletal debris

CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm

Well : E-5X
Core : 4

Scale : c 1:10
Geologist / Logging date : Jl, 3/2003



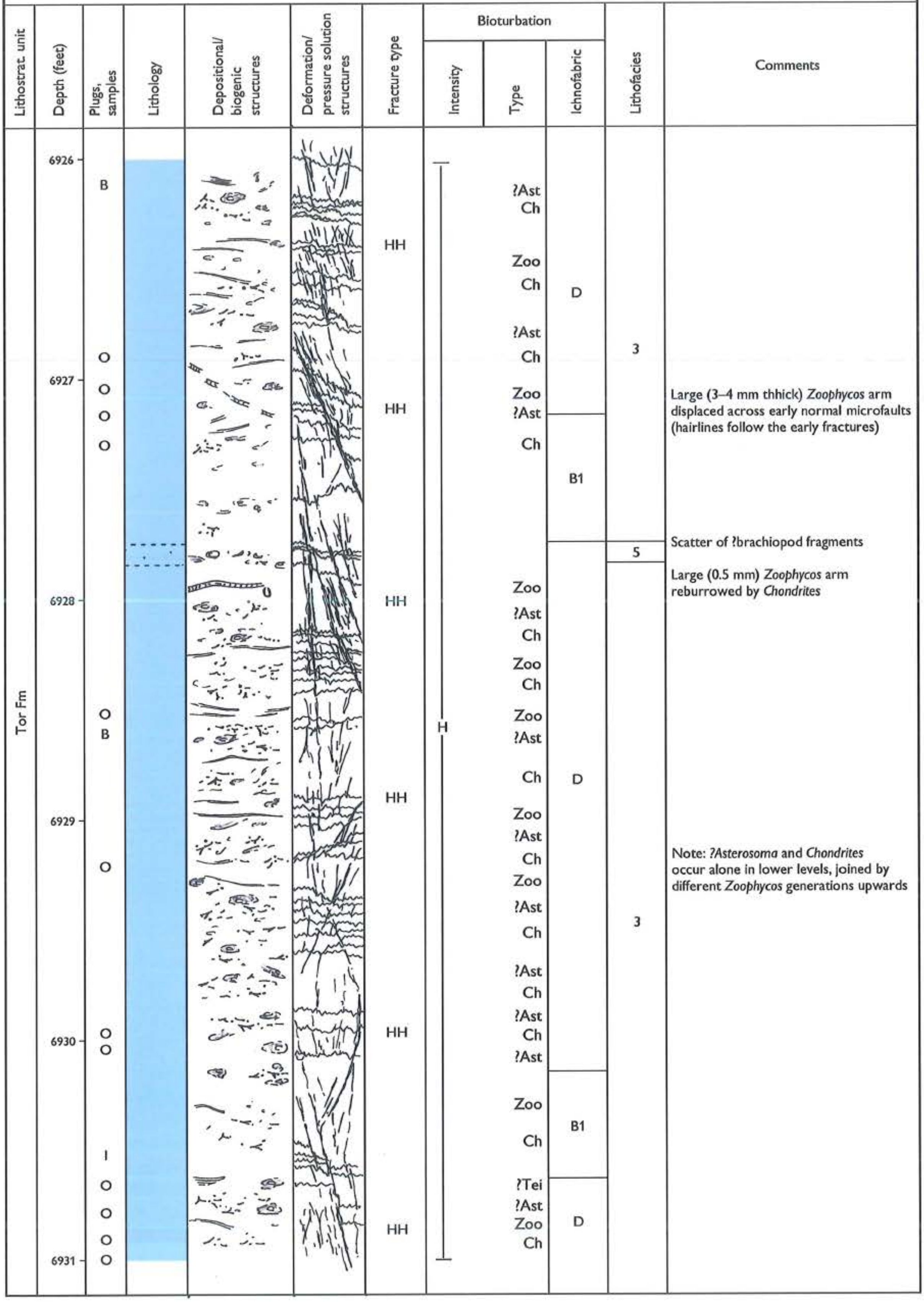
Lithostrat. unit	Depth (feet)	Plugs, samples	Lithology	Depositional/ biogenic structures	Deformation/ pressure solution structures	Fracture type	Bioturbation Intensity	Bioturbation Type	Ichnofabric	Lithofacies	Comments
Tor Fm	6921							Ch			Intense hairlines along early fracture; dilation fractures
						HH	H	?Ast	B1	3	
	6922										
	6923										
								Ch			Large *Zoophycos* cuts smaller forms
	6924							Zoo			
						HH					
								?Ast			
		o				SA		Zoo			
								Ch			
								Zoo			Stylolite-associated fractures more oil-stained than hairlines
								?Ast			
						HH		?Ast			
		o					H	?Pla			
	6925					SA		Zoo	D	3	
								Ch			
								Zoo			
								?Ast			
		o				HH		Zoo			
								Ch			
	6926										

CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm

Well : E-5X
Core : 4

Scale : c 1:10
Geologist / Logging date : Jl, 3/2003



Large (3–4 mm thhick) *Zoophycos* arm displaced across early normal microfaults (hairlines follow the early fractures)

Scatter of ?brachiopod fragments

Large (0.5 mm) *Zoophycos* arm reburrowed by *Chondrites*

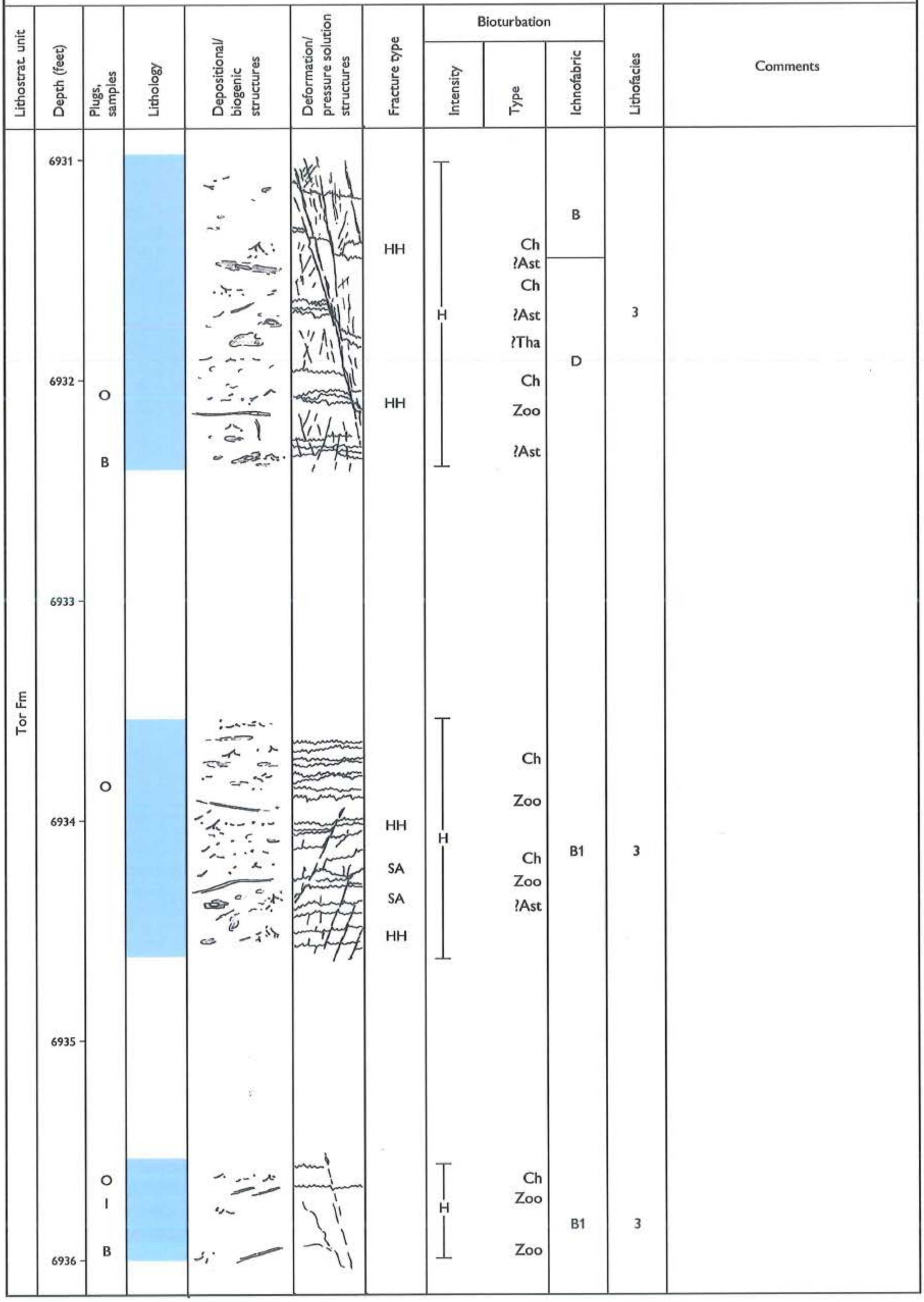
Note: ?*Asterosoma* and *Chondrites* occur alone in lower levels, joined by different *Zoophycos* generations upwards

CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm

Well : E-5X
Core : 4

Scale : c 1:10
Geologist / Logging date : Jl, 3/2003

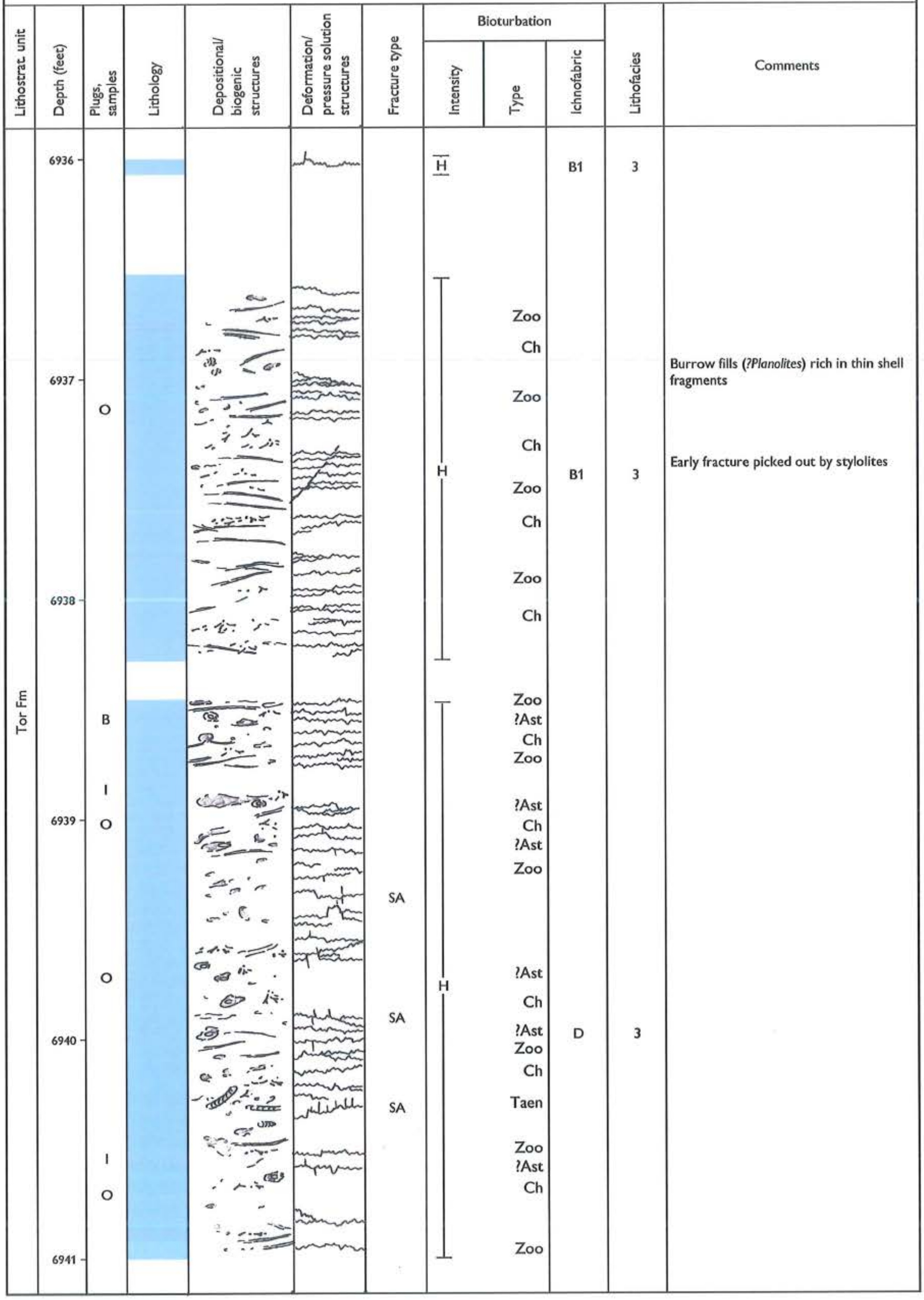


CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm

Well : E-5X
Core : 4

Scale : c 1:10
Geologist / Logging date : Jl, 3/2003



Burrow fills (*?Planolites*) rich in thin shell fragments

Early fracture picked out by stylolites

CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm

Well : E-5X
Core : 4

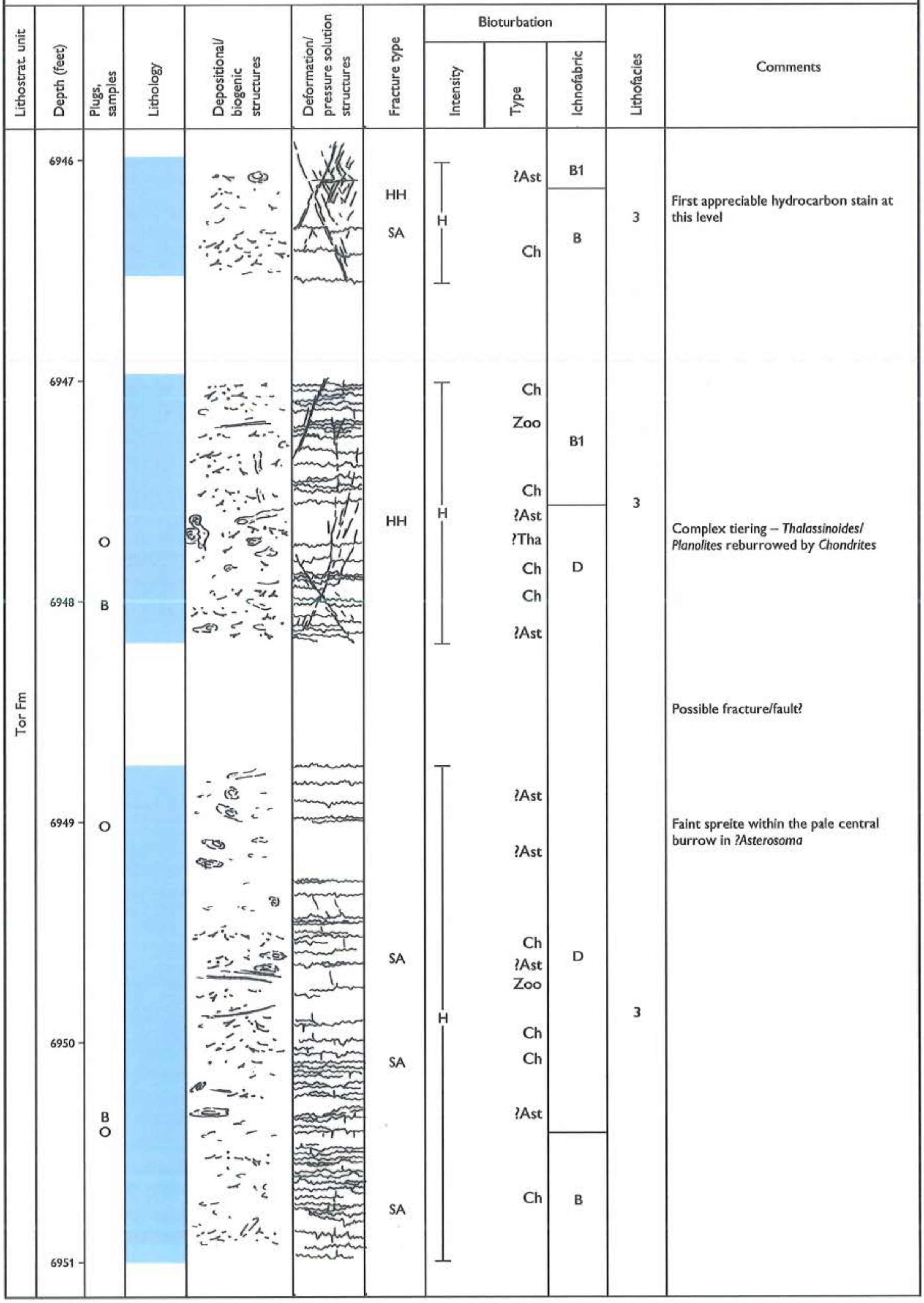
Scale : c 1:10
Geologist / Logging date : Jl, 3/2003

CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm

Well : E-5X
Core : 4

Scale : c 1:10
Geologist / Logging date : Jl, 3/2003



First appreciable hydrocarbon stain at this level

Complex tiering – *Thalassinoides*/ *Planolites* reburrowed by *Chondrites*

Possible fracture/fault?

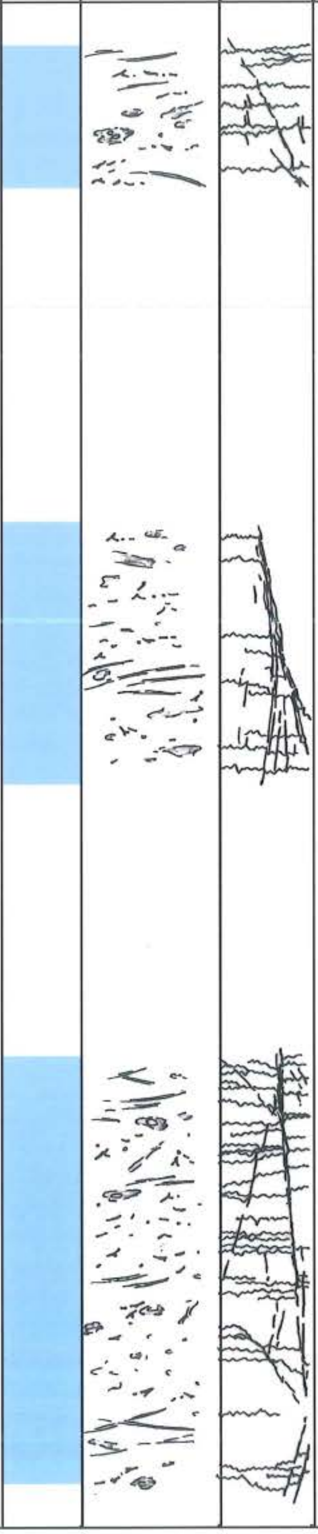
Faint spreite within the pale central burrow in *?Asterosoma*

CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm

Well : E-5X
Core : 4

Scale : c 1:10
Geologist / Logging date : Jl, 3/2003



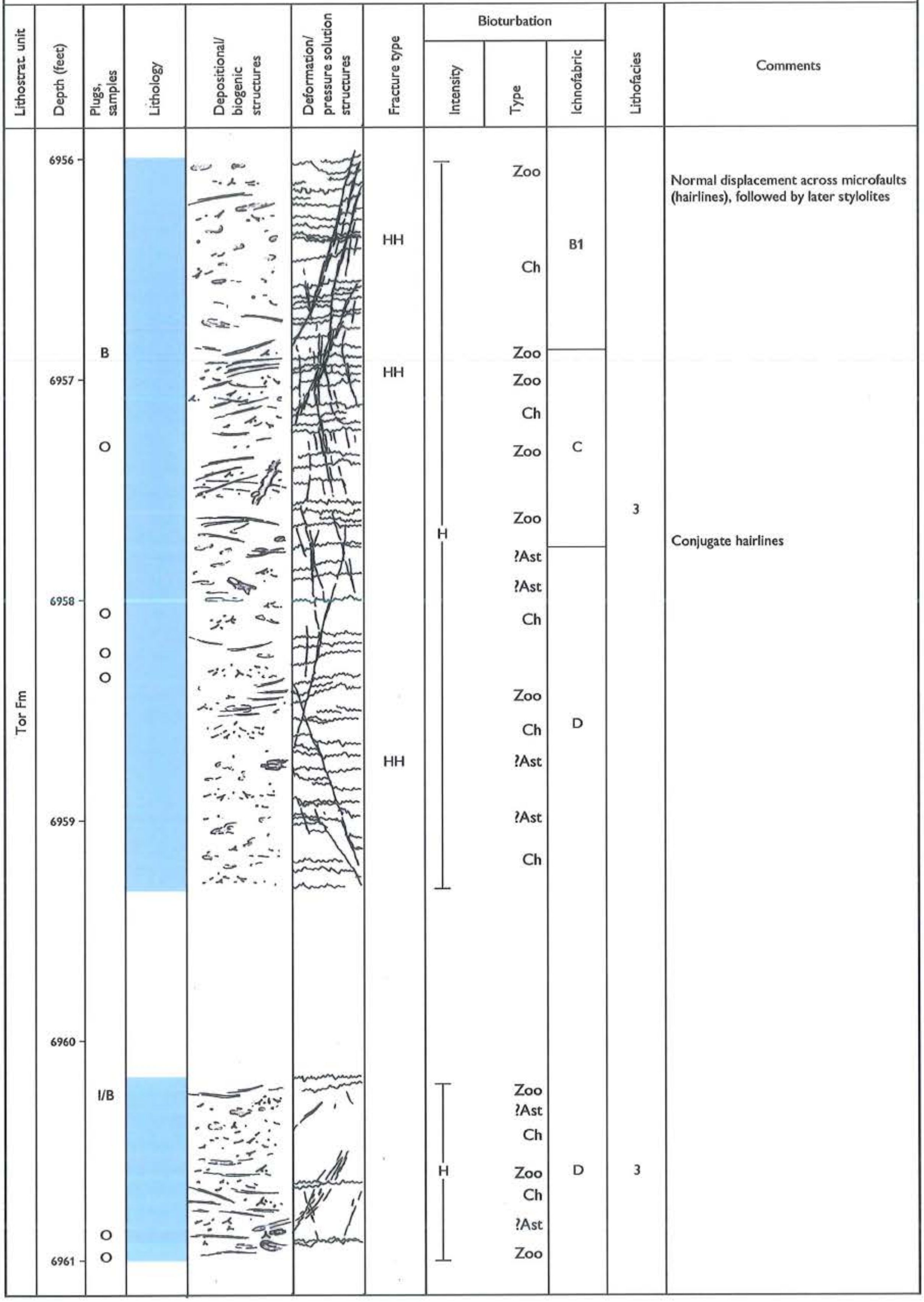
Lithostrat. unit	Depth (feet)	Plugs, samples	Fracture type	Bioturbation Intensity	Bioturbation Type	Ichnofabric	Lithofacies	Comments
Tor Fm	6951	I	SA	H	Zoo Ch ?Ast Ch	D	3	Several pale spreited burrows in single *?Asterosoma* mantle
	6952							Possible fracture/minor fault at this level?
	6953	B	HH	H	Ch Zoo	B1	3	RHS of slabbed core absent
	6954							
	6955	I O O	HH HH	H	Zoo ?Ast Ch ?Ast Ch Zoo ?Ast Ch Zoo ?Ast	D	3	
	6956							

CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm

Well : E-5X
Core : 4

Scale : c 1:10
Geologist / Logging date : Jl, 3/2003



Normal displacement across microfaults (hairlines), followed by later stylolites

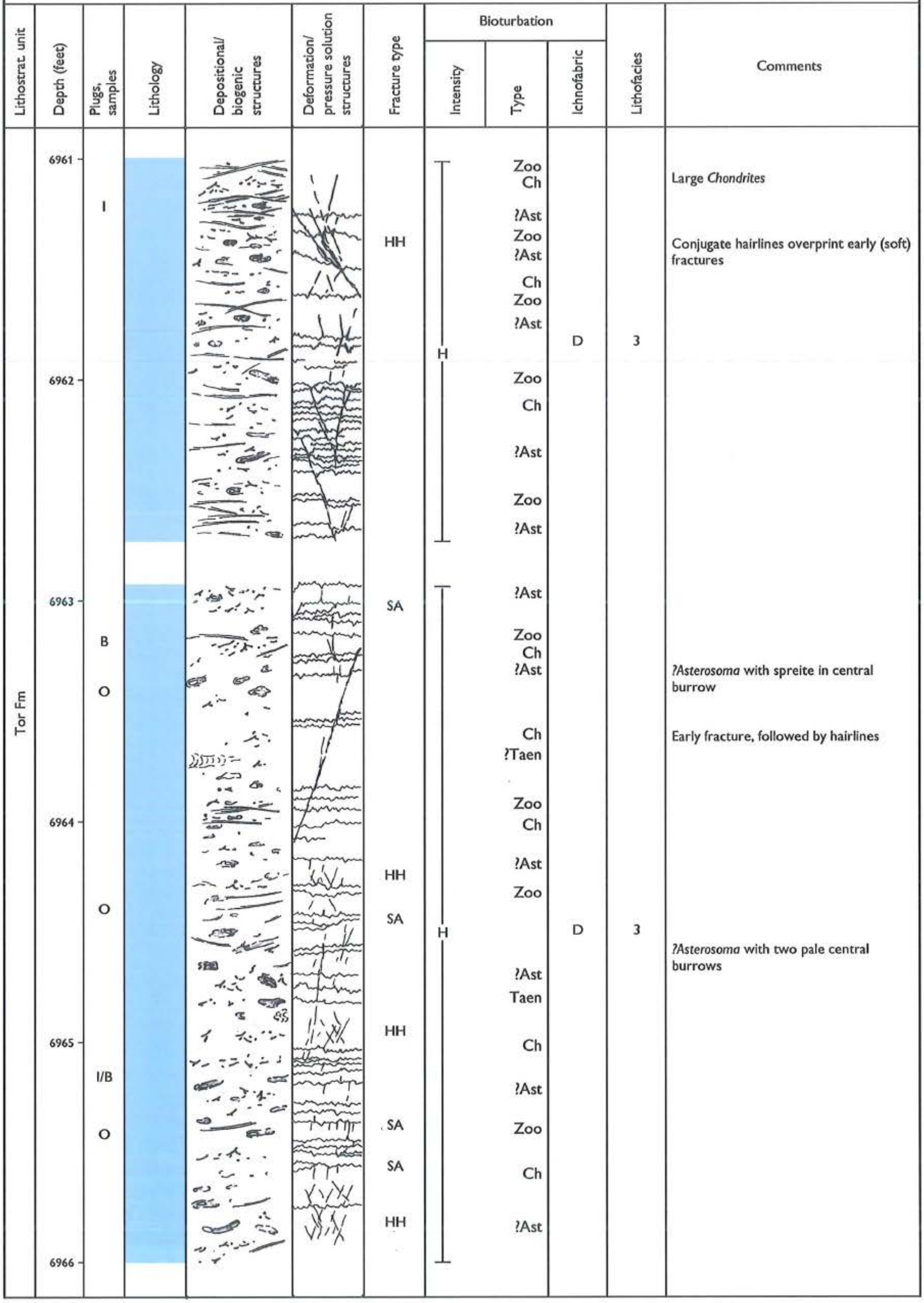
Conjugate hairlines

CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm

Well : E-5X
Core : 4

Scale : c 1:10
Geologist / Logging date : Jl, 3/2003



Large *Chondrites*

Conjugate hairlines overprint early (soft) fractures

?Asterosoma with spreite in central burrow

Early fracture, followed by hairlines

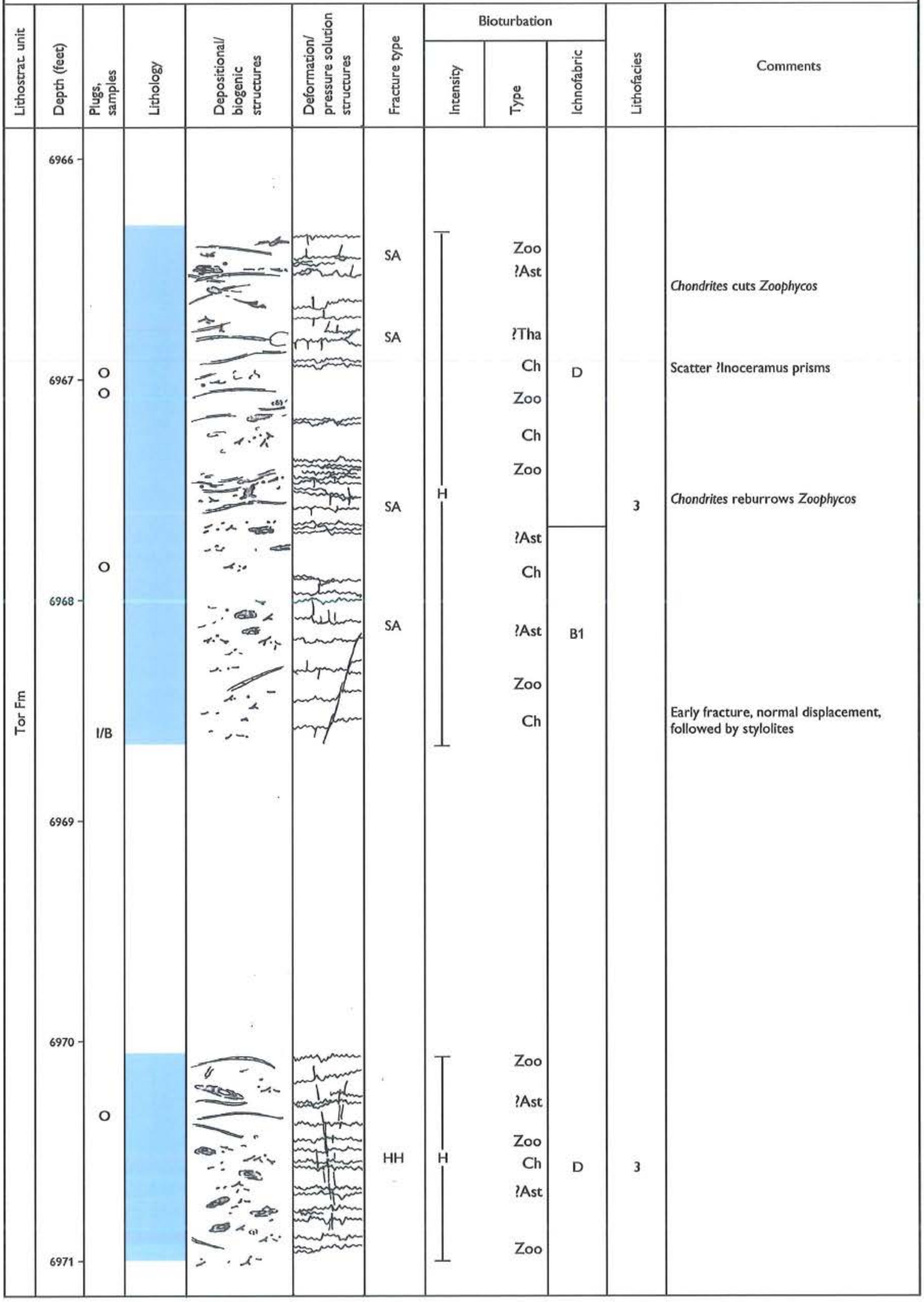
?Asterosoma with two pale central burrows

CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm

Well : E-5X
Core : 4

Scale : c 1:10
Geologist / Logging date : Jl, 3/2003



Chondrites cuts *Zoophycos*

Scatter ?Inoceramus prisms

Chondrites reburrows *Zoophycos*

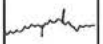
Early fracture, normal displacement, followed by stylolites

CORE DESCRIPTION

Field / Area : Tyra SE
Lithostrat. unit : Tor Fm

Well : E-5X
Core : 4

Scale : c 1:10
Geologist / Logging date : Jl, 3/2003

Lithostrat. unit	Depth (feet)	Plugs, samples	Lithology	Depositional/ biogenic structures	Deformation/ pressure solution structures	Fracture type	Bioturbation			Lithofacies	Comments
							Intensity	Type	Ichnofabric		
Tor Fm	6971 6972	O I B				HH	H	?Ast Ch ?Ast Ch ?Ast Ch Zoo	D	3	Abundant *?Asterosoma* – locally cut by *Zoophycos*
	6973	O					H	Ch	B	3	
	6974 6975	I B				HH	H	Ch ?Tha Pla Zoo Ch Zoo	D	3	*?Inoceramus* prisms
	6976										