

core samples have been available. As the use of stratigraphic lowest occurrences (LO) of taxa in cuttings samples may be hampered due to downhole caving, the event succession comprises almost exclusively stratigraphic highest occurrences (HO) of taxa (a single significant LO is included in the succession). The event succession is shown in Fig. 5a–c; its correlation with international and North Sea biozones is shown in Fig. 6a–c.

Seismic sections from the 2-D and 3-D seismic surveys CGD85, DK-1, RTD81–RE94, UCG96 and UCGE97 have been used to further support the well correlation and to map the stratigraphic units in areas with only scattered well coverage. The combined results from the correlation and mapping procedures are presented as isochore maps for individual stratigraphic units.

Inspection of cuttings samples from 16 key wells supplemented with sedimentological studies of cored inter-

vals from 23 wells have formed the basis for the lithological and sedimentological descriptions of the units.

The well depths mentioned in the lithostratigraphy section are loggers' depths measured either from rotary table (MDRT) or kelly bushing (MDKB). Supplementary data for new type and reference wells are provided in Table 1.

The names assigned to the new lithostratigraphic units defined herein are derived from Nordic mythology and thus follow the nomenclatural tradition previously established for the Norwegian North Sea (Isaksen & Tonstad 1989).

It should be noted that the micropalaeontology-based palaeoenvironmental terminology used herein was originally developed for a passive margin situation (e.g. the terms 'neritic' and 'bathyal' to indicate the physiographic zones 'shelf' and 'shelf-slope', respectively). Its application herein to the epicontinental North Sea Basin solely relates to depositional depth.

Offshore and onshore lithostratigraphic nomenclature

There is a high degree of lithological similarity between the Palaeogene–Neogene mudstone succession in Danish offshore boreholes and that in onshore exposures and boreholes. However, the status of the Danish onshore units is quite varied since many units were named before a standard for description of a lithostratigraphic unit was established; some fulfil these requirements, whereas others are still informal. If a previously established onshore unit and an offshore unit can be demonstrated to be identical (e.g. the Holmehus Formation and the new Ve Member proposed herein), the name of the onshore unit theoretically has priority over the name of the offshore unit (Salvador 1994). In other cases, names of offshore units can be argued to have priority over onshore units (e.g. Sele and Balder Formations over Ølst Formation). However, in order to acknowledge the traditional distinction between offshore and onshore stratigraphic nomenclature, the two sets of nomenclature are kept separate herein. Whenever possible, comments are given in the text to explain the relationship between offshore and onshore Danish stratigraphic nomenclature. A correlation between the two sets of nomenclature is shown in Fig. 2.

Chronostratigraphy and biostratigraphy

Age assessment of the lithostratigraphic units in the North Sea sedimentary succession is based on correlation between key biostratigraphic events encountered in the units and the calibrated standard chronostratigraphy published by Berggren *et al.* (1995), with modification for the Paleocene–Eocene boundary following ratification of its position by the International Union of Geological Scientists (Aubry *et al.* 2002). The key events are from biostratigraphic zonation schemes established for the North Sea area. Planktonic and benthic microfossils are covered by the zonation schemes of King (1983, 1989; Figs 5a–c, 6a–c). Dinoflagellates from the Paleocene and Eocene Epochs are covered by the zonation scheme of Mudge & Bujak (1996b; Fig. 6a, b); the Oligocene and Miocene Epochs are covered by the zonation schemes of Costa & Manum (1988) with modifications by Köthe (1990, 2003; Fig. 6b, c). Key events from these schemes used in this study are listed in Fig. 5a–c.

For the dinoflagellate events, geochronological calibration has been largely established using age estimates from Hardenbol *et al.* (1998), Munsterman & Brinkhuis (2004) and Williams *et al.* (2004). For events not mentioned in these three publications, the works of Mudge & Bujak

b Geo- chronology Ma	Chronostratigraphy (Berggren et al. 1995)		Standard biozones		North Sea biozones				
			Berggren & Miller (1988), Berggren et al. (1995)	Martini (1971)	King (1989)		Costa & Manum (1988), Köthe (1990), Mudge & Bujak (1996b)		
	Series	Stage	Planktonic microfossils	Calcareous nanofossils	Planktonic microfossils	Benthic microfossils	Dinoflagellate cysts		
35	Oligocene (pars)	Lower (pars)	Rupelian (pars)	P19 (pars)	Np23 (pars)	NSP9b	NSB7a	D13 ↑ Costa & Manum (1988), Köthe (1990) Mudge & Bujak (1996b) ↓ E8b	
				P18	NP22				
40	Eocene (pars)	Upper	Priabonian	P17	NP21	NSP9a	NSB6b		
				P16	NP19–20	NSP8c	NSB6a		
			Bartonian	P15	NP18	NSP8b	NSB5c		
				P14	NP17	NSP8a	NSB5b		
P13	NP16								
45	Middle	Lutetian	P12	NP15	NSP7	NSB5a	E7b		
			P11				E7a		
			P10	NP14			E6c		
		Ypresian (pars)	P9	NP13	NSP6	NSB4	E6b		
			P8				E6a		
			P7	NP12			E5b	E5a	
50	Lower (pars)	Ypresian (pars)	P6	b	NSP5b	NSB3b	E4d		
				a			NP11	E4c	
							Np10 (pars)	E4b	
							NSP4 (pars)	NSB2 (pars)	E4a
									E3d
									E3c
				E3b					
				E3a					
				NSP5a	NSB3a	E2c			
						E2b			
						E2a			
						E1c	E1b		
						E1a (pars)			

Fig. 6b. Eocene–Oligocene biostratigraphic correlation chart.

c Geo- chronology Ma	Chronostratigraphy (Berggren et al. 1995)		Standard biozones		North Sea biozones						
			Berggren & Miller (1988), Berggren et al. (1995)	Martini (1971)	King (1989)		Costa & Manum (1988), Köthe (1990),				
	Series	Stage	Planktonic microfossils	Calcareous nannofossils	Planktonic microfossils	Benthic microfossils	Dinoflagellate cysts				
15	Miocene (<i>pars</i>)	Upper (<i>pars</i>)	Tortonian (<i>pars</i>)	M13a (<i>pars</i>)	NN9b (<i>pars</i>)	NSP14b	NSB13a	D19			
			11.2	M12	NN9A– NN7						
				M10 M11							
		Middle	Serravallian	M9	NN6	NSP14a	NSB12c	D18			
				M8		NSP13	NSB12b				
				M7		NSB12a					
		14.8	M6	NN5	NSP12	NSB11	D17				
		Langhian	M5	NN4	NSP11	NSB10					
			M4								
	Lower	Burdigalian	M3	NN3	NSP10	NSB9	D16				
			20.5	M2				NN2			
			Aquitanian	M1				b	NN1	NSB8c	
	a										
	25	Upper	Chattian	P22	NP25	NSP9c	NSB8b	D15			
				28.5	P21				b	NP24	NSB8a
									a		
		Lower (<i>pars</i>)	Rupelian (<i>pars</i>)	P20	NP23	NSP9b	NSB7b	D14			
				P19							
P18				NP22					NSP9a (<i>pars</i>)	NSB6b (<i>pars</i>)	D13
NP21 (<i>pars</i>)											

Fig. 6c. Oligocene – Middle Miocene biostratigraphic correlation chart.

(1996b), Dybkjær (2004), Piasecki (2005) and Schiøler (2005) have been consulted. However, whereas Hardenbol *et al.* (1998) and Williams *et al.* (2004) used the timescale of Berggren *et al.* (1995), Mudge & Bujak used the slightly older timescale from Haq *et al.* (1987) for calibration of their events. Therefore, the ages of events only listed by Mudge & Bujak have been recalibrated herein to conform to the timescale of Berggren *et al.* (1995).

King (1989) calibrated his planktonic and benthic microfossil zone markers with the standard chronostratigraphic scale of Berggren *et al.* (1985a, b). However, King noted that only a few first-order correlations were possible; most of the calibrations were made using dinoflagellates, planktonic foraminifers and nannoplankton from onshore sections in the North Sea Basin (King 1989 p. 420); the correlation of the Lower Miocene is particularly uncertain (King 1989 p. 446). Paleocene and Eocene key planktonic and benthic microfossil events from King (1989) were subsequently correlated with the North Sea dinoflagellate events by Mudge & Bujak (1996b). By using the above-mentioned recalibration of key dinoflagellate events from Mudge & Bujak (1996b), it is feasible to indirectly correlate King's North Sea microfossil events with the timescale of Berggren *et al.* (1995). This has been attempted in Fig. 5a–c.

Figure 6a–c shows the relationships between the North Sea biozones and their correlation with the standard planktonic foraminifer and calcareous nannofossil zones. However, it should be noticed that in a few cases the correlation of the North Sea microfossil and dinoflagellate zones with the standard zones in Fig. 6a–c is at variance with that of the authors of the same zones. This is an effect of improved age determinations of the standard zones and the dinoflagellate events used to calibrate the North Sea microfossil zones.

The section below outlines the current status for the Palaeogene and Neogene chronostratigraphic units covered by the studied succession and lists key biostratigraphic events used for chronostratigraphic correlation of the succession.

Paleocene

The bases of the Selandian and Thanetian Stages, which together constitute the Upper Paleocene Series, have yet to be formally defined. However, ongoing work in the International Subcommittee on Palaeogene Stratigraphy indicates that the Global Standard Stratotype-section and Point (GSSP) of the base of the Selandian Stage will probably be close to the P2–P3a or the P3a–P3b standard planktonic foraminifer zone boundary, while the GSSP

for the Thanetian Stage will probably be at the base of Magnetochron C26n (Gradstein & Ogg 2002). Hardenbol *et al.* (1998) followed Berggren *et al.* (1995) in placing the base of the Selandian Stage at the base of Zone P3a, at the lowest occurrence of the planktonic foraminifer *Morozovella angulata*. However, many of the microfossil species that characterise the Danian–Selandian boundary interval in the international zonation schemes, including *M. angulata*, are extremely rare or absent in the North Sea Basin thereby hampering chronostratigraphic correlation of the boundary. Based on a study of core material from the type area for the Danian and Selandian Stages, Clemmensen & Thomsen (2005) concluded that the Danian–Selandian stage boundary is located in the upper part of the NP4 standard nannofossil zone, close to the NP4–NP5 zone boundary, approximately at the P3a–P3b zone boundary, at *c.* 60 Ma on the timescale of Hardenbol *et al.* (1998). They further concluded that there is a hiatus between the Danian and Selandian Stages in the Danish area outside the Central Graben due to truncation of the Danian limestones of the Ekofisk Formation (Fig. 5a; Clemmensen & Thomsen 2005). Hence, the Danian–Selandian stage boundary is herein placed just below the downhole reappearance (provisional HO) of planktonic foraminifers and the HO of the dinoflagellate *Alisocysta reticulata*, but above the closely spaced events marked by the HO of the planktonic foraminifers *Subbotina trivialis* and *Globanomalina cf. compressa* (e.g. Jones 1999; Mudge & Bujak 2001).

The Selandian–Thanetian stage boundary is herein approximated by the HO of the dinoflagellate *Palaeopetridinium pyrophorum*, at the base of the P5 dinoflagellate Zone of Mudge & Bujak (1996b). This level is close to the base of Magnetochron C26n, according to Hardenbol *et al.* (1998).

Eocene

The base of the Eocene is at the base of the negative carbon isotope excursion (CIE) at 55.5 Ma (Berggren & Aubry 1996; Aubry *et al.* 2002). This position is below the base of the Ypresian Stage, the lowermost Eocene Stage. Therefore it has been proposed to reintroduce the Sparnacian Stage as the new basal Eocene Stage between the CIE and the base of the Ypresian (Aubry *et al.* 2003). The CIE has been correlated with the proliferation of the dinoflagellate genus *Apectodinium*, an event recognised globally (e.g. Knox 1996; Crouch *et al.* 2001). Onshore Denmark, the CIE and the proliferation of *Apectodinium* coincides precisely with the laminated Stolle Klint Clay in the

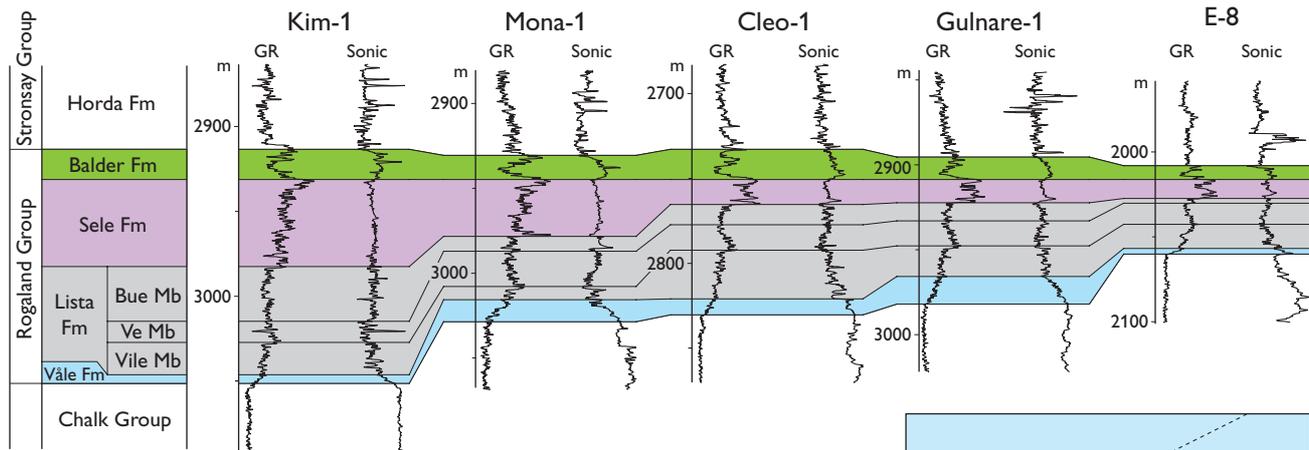
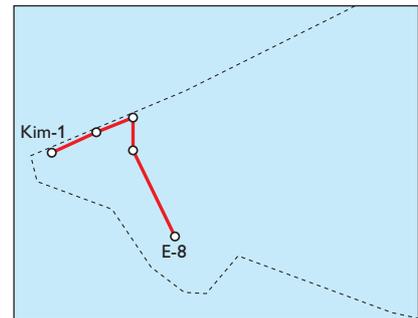


Fig. 7. Log panel illustrating the thickness variation of the Rogaland Group formations in the Danish Central Graben.



lowermost part of the Haslund Member of the Ølst Formation (Heilmann-Clausen & Schmitz 2000; Willumsen 2004). In the North Sea Basin, the acme of *Apectodinium* is located in the lowermost, laminated part of the Sele Formation (*sensu* Deegan & Scull 1977, see below) according to Knox (1996). As the event is a LO, its position cannot be determined with certainty in wells in which this interval is covered only by cuttings samples. In the North Sea Basin, however, this stratigraphic level is characterised by a prominent excursion on the gamma-ray log near the base of the Sele Formation which therefore can be used as an approximation for the base of the Eocene Series.

The remaining stages of the Eocene Series, the Ypresian, Lutetian, Bartonian and Priabonian Stages, lack basal boundary GSSPs for the present. In this paper, we follow Mudge & Bujak (1996b) and approximate the bases of the three latter stages by using three key dinoflagellate events: the base of the Lutetian Stage is at the HO of common *Eatonicysta ursulae*, the base of the Bartonian Stage is close to the HO of *Diphyes colligerum*, and the base of the Priabonian Stage is close to the HO of *Heteraulacacysta porosa*. The base of the classic Ypresian Stage is at the LO of the calcareous nannoplankton species *Tribrachiatus digitalis*. As yet, there is no commonly recognised HO index event at that level in the North Sea Basin, but the boundary between the Sparnacian and the Ypresian Stages may be placed below the HOs of com-

mon *Cerodinium wardenense* and *Apectodinium augustum* (Fig. 5a), both dinoflagellate species.

Oligocene

The GSSP for the Eocene–Oligocene boundary is in the Massignano section (central Italy), at the highest occurrence of the planktonic foraminifer genera *Hantkenina* and *Cribohantkenina*, immediately above the P17–P18 planktonic foraminifer zone boundary (Premoli Silva & Jenkins 1993). However, hantkeninids have not been observed from the North Sea Basin and alternative zone markers have therefore been used here. In the North Sea Basin, the planktonic foraminifer *Globigerinatheka index* and the benthic foraminifer *Cibicidoides truncanus* have their HOs in the uppermost Eocene (King 1989), and the two events may be used to approximate the Eocene–Oligocene boundary. A palynological marker of the lowermost Oligocene is the HO of the dinoflagellate *Areosphaeridium diktyoplokum* (Brinkhuis & Biffi 1993; Brinkhuis & Visscher 1995), which is widespread in the North Sea Basin. The three latter events in combination serve as useful markers for bracketing the Eocene–Oligocene boundary in the North Sea Basin.

The principal criterion for the Rupelian–Chattian (Lower–Upper Oligocene) boundary has not yet been de-

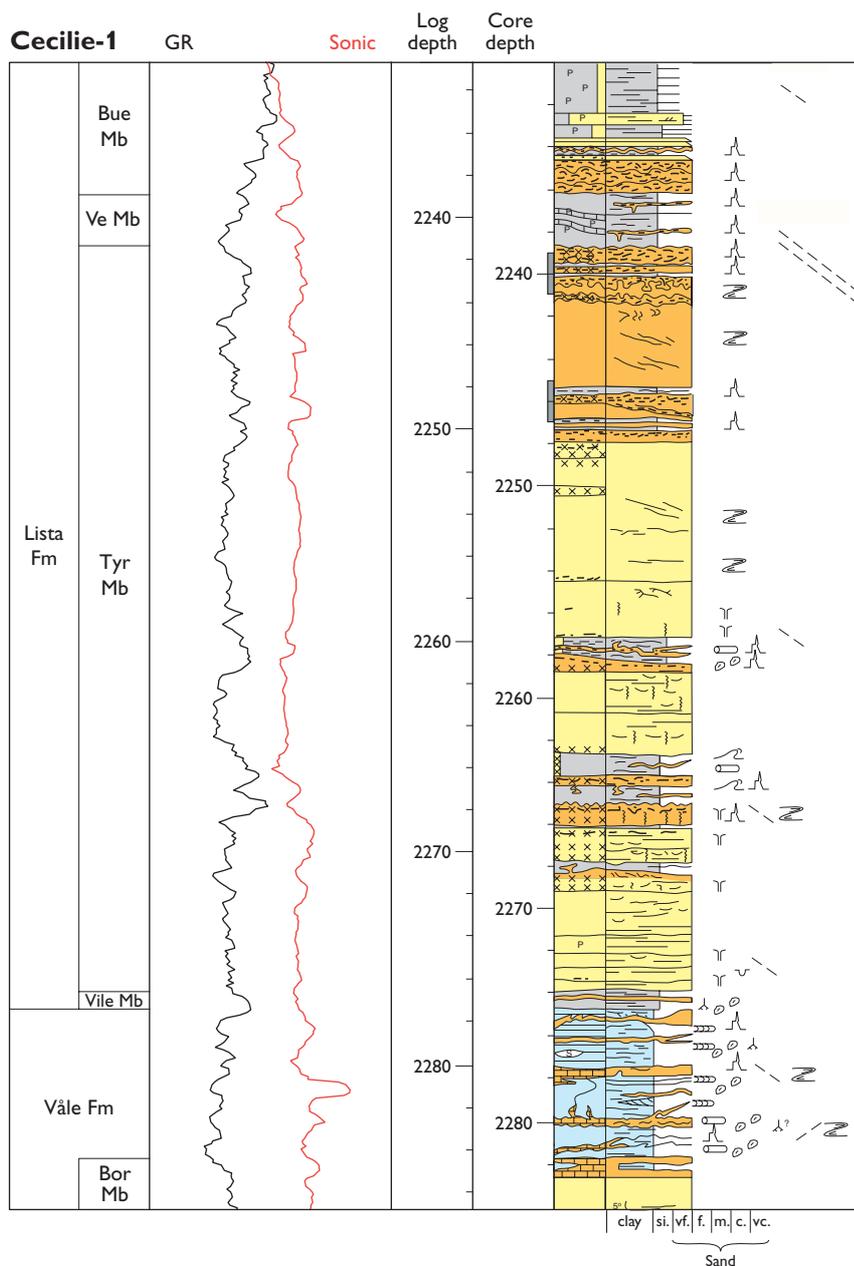


Fig. 8. Core log showing intrusive sandstones in the Våle and Lista Formations in the Cecilie-1 well. For legend, see Fig. 9. The two intervals marked by grey bars in the core depth column are shown as core photographs in Fig. 10.

cided by the Subcommittee on Palaeogene Stratigraphy. Indications are that the boundary may be positioned at the base of the P21b planktonic foraminifer zone (Premoli Silva 2005), at 28.5 Ma (Hardenbol *et al.* 1998). However, the defining boundary event cannot be recognised in the North Sea Basin and its exact correlation with the North Sea biostratigraphic event succession remains uncertain. Instead, most North Sea biostratigraphers recognise the Rupelian– Chattian stage boundary at the HO of the benthic foraminifer *Rotaliatina bulimoides*. This event marks the top of the NSB7 Zone of King (1983, 1989; Fig. 5c) and the NSR7 Zone of Gradstein *et al.* (1994). The HO of *R. bulimoides* is at 29 Ma in the northern

North Sea according to Gradstein & Bäckström (1996), slightly older than the 28.5 Ma for the Rupelian– Chattian stage boundary quoted by Hardenbol *et al.* (1998). The Rupelian– Chattian stage boundary may also be approximated by the HO of the dinoflagellate *Rhombodinium draco*. In the North Sea wells reported herein, where both the HOs of *R. bulimoides* and *R. draco* have been recorded, these events are largely contemporaneous. However, in the type area of the Rupelian and Chattian Stages, *R. draco* has its HO above *R. bulimoides* in the type Chattian (van Simaey *et al.* 2004). Therefore, it may be inferred that the two latter events probably bracket the Rupelian– Chattian boundary (Fig. 5c).

Miocene

The Oligocene–Miocene Series boundary is bracketed by a number of HOs at its type section (Lemme-Carosio, north-west Italy). Unfortunately, none of the foraminifer events are believed to be true stratigraphic tops (facies dependent), and reworking in the section hampers the use of nannofossil tops (Steininger *et al.* 1997). However, the dinoflagellate succession from the Lemme-Carosio section has been documented in detail by Powell (1986), Brinkhuis *et al.* (1992) and Zevenboom (1995, 1996), and provides a means for direct correlation to the North Sea Basin (Munsterman & Brinkhuis 2004). The HO of *Distatodinium biffii* is below the Chattian–Aquitanian boundary in its type section and the HO of *Chiropteridium* spp. is above. This succession of events can be recognised in many North Sea wells, and the Chattian–Aquitanian boundary is positioned between the two. Supporting microfossil events that characterise the lowermost Miocene include the HO of the diatom *Aulacodiscus insignis quadrata* (small morphotype, same as diatom sp. 3 of King 1983, 1989), a widespread event in the North Sea Basin, and the HO of the benthic foraminifer *Brizalina antiqua* (King 1989). The HO of the planktonic foraminifer *Paragloborotalia nana* marks uppermost Chattian strata.

The principal criteria for the Aquitanian–Burdigalian, Burdigalian–Langhian and Langhian–Serravallian stage boundaries are as yet undecided. Most authors place the three boundaries at microfossil zone boundaries or magnetochron boundaries at 20.5, 16.4 and 14.8 Ma, respectively (Hardenbol *et al.* 1998; Williams *et al.* 2004). The correlation of the three boundaries to the North Sea Basin is feasible using the dinoflagellate zonation scheme of De Verteuil & Norris (1996), established for US East Coast sections and the review of dinoflagellate index events published by Williams *et al.* (2004). The former zonation scheme is correlated directly with the zonation schemes of Berggren *et al.* (1995) and the Miocene timescale by means of calcareous nannofossils and foraminifers. The Aquitanian–Burdigalian boundary is positioned just above the HO of the dinoflagellate *Caligodinium amiculum*. The Burdigalian–Langhian boundary is placed between the HO of the dinoflagellates *Hystrichokolpoma cinctum* and *Pyxidinospis fairhavenensis*, two events that bracket the boundary level. The Langhian–Serravallian boundary is slightly above the HO of the dinoflagellate *Coosteaudinium aubryae*. In this study, these four events have been used to approximate the three stage boundaries.

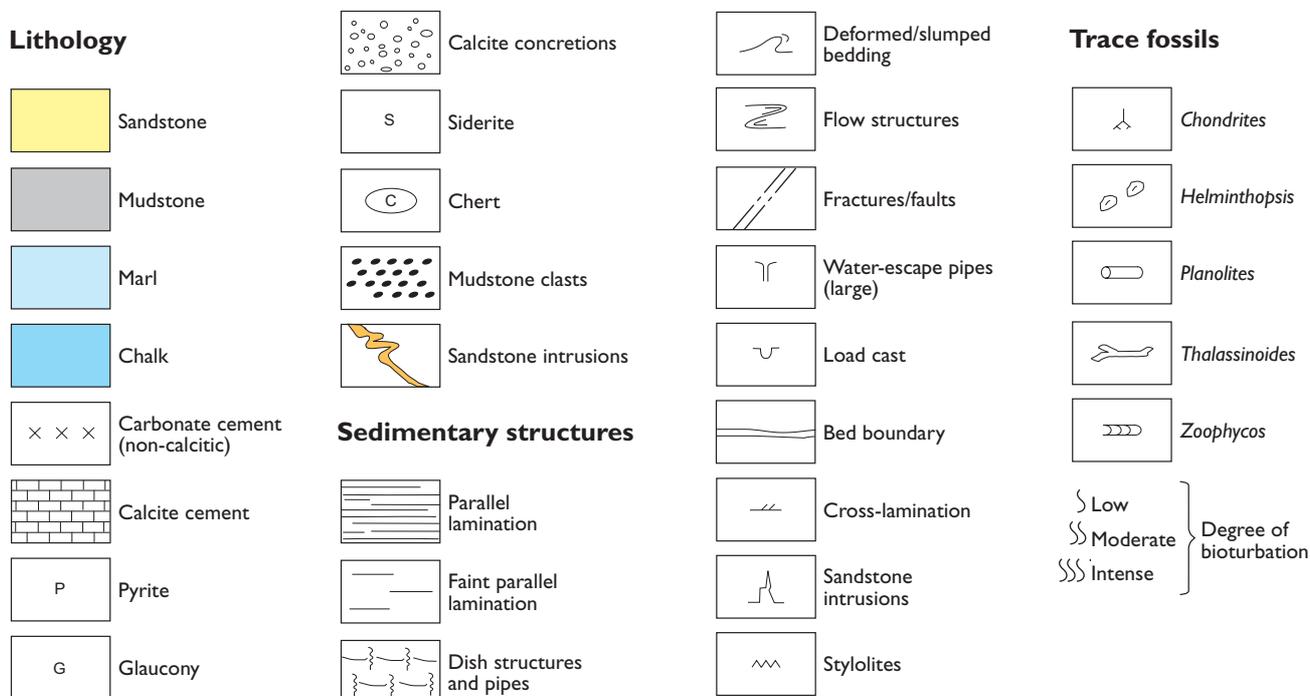


Fig. 9. Legend for core logs (Figs. 8, 11, 18, 27, 30 and 39); the lithological colour scheme is also adopted on well sections (e.g. Fig. 13).