PROCEEDINGS OF THE YORKSHIRE GEOLOGICAL SOCIETY, VOL. 56, PART 3, PP. 159–176, 2007

The ammonite succession in the 'Oxford Clay' at South Cave Station Quarry, Yorkshire

K. J. PHIPPS

Department of Geography, University of Hull, Cottingham Road, Kingston upon Hull, Yorkshire HU6 7RX, U.K.

SUMMARY: The argillaceous succession at South Cave Station Quarry, East Yorkshire, historically described as the Oxford Clay, can be divided into the Callovian Oxford Clay Formation (upper part of the Peterborough Member and the Stewartby Member) and the Brantingham Formation of Oxfordian age. Of the standard Jurassic chronostratigraphical zones, the Coronatum Zone may be present as a thin bed of clayey sandstone at the base of the Oxford Clay Formation. The overlying beds of this formation belong to the Athleta Zone (Phaeinum and Proniae subzones), and the Brantingham Formation at South Cave Station Quarry belongs to the Cordatum Subzone of the Cordatum Zone. Two significant non-sequences have been recorded. The lower non-sequence, spanning the Jason Zone and perhaps part of the Coronatum Zone, is also present in North Yorkshire and Lincolnshire. The higher non-sequence, from the Spinosum Subzone of the Athleta Zone to the Costicardia Subzone of the Cordatum Zone, appears to be restricted to the South Cave and the Acklam area, near Malton, in North Yorkshire. Clear links have been established between the ammonite assemblages of the Proniae Subzone at South Cave and those at Peckondale Hill and Acklam, both near Malton, and in the area between Peterborough and Oxford.

The main outcrop of the Oxford Clay Formation in England stretches from the Dorset coast of southern England to north-east Yorkshire, and the succession ranges in age from youngest Early Callovian to Early Oxfordian. A tripartite division into Lower, Middle and Upper Oxford Clay was used for many years, but these terms have been superseded respectively by the Peterborough, Stewartby and Weymouth members (Cox *et al.* 1992). The lithostratigraphy and associated ammonite-based chronostratigraphical zones and subzones are shown in Figure 1.

Although the Oxford Clay Formation from Dorset to the Humber is argillaceous, sandy deposits dominate the succession in north-east Yorkshire. The Peterborough and Stewartby members are present in Yorkshire as far north as Malton (Wright 1968*b*), but only the Weymouth Member has been recorded farther north, in the Cleveland Basin (Rawson & Wright 1995, p. 183). There, the equivalents of the Peterborough and Stewartby members are the silty sandstones and shallow water carbonates of the Osgodby Formation (Wright 1978).

The Oxford Clay Formation in East Yorkshire is poorly exposed and best known from cored boreholes that have yielded some ammonites (Gaunt *et al.* 1980). The fauna of the Oxford Clay in this region has not been described in detail. A comprehensive study of the palaeontology and stratigraphy of the Oxford Clay at South Cave Station Quarry, based on temporary sections and pit excavations, was carried out by the author between 1998 and 2001. This paper provides a summary of the ammonite succession at the site and enhances the previously described zonal stratigraphy of the Callovian succession in the area.

1. SOUTH CAVE STATION QUARRY

South Cave Station Quarry [SE 920 329] lies on the south side of Drewton Dale, approximately 2 km NNW of South Cave village (Fig. 2). The quarry is located on the western edge of the Yorkshire Wolds escarpment, where the narrow outcrop of Jurassic rocks is overstepped by Cretaceous strata. The excavation of a railway cutting here in 1881 revealed a sequence through the Kellaways Formation and Oxford Clay. Keeping & Middlemiss (1883) provided the first published account of the exposures, and their observations were included in subsequent publications. These early papers refer to the location as either 'Drewton Cutting' (Fox-Strangways 1892) (Fig. 2) or 'cuttings . . . east of South Cave Station' (Sheppard 1903).

The 'Kellaways Sands', now the Kellaways Sand Member of the Kellaways Formation (Page 1989), were used in the production of moulds for engineering castings, and a pit to the north of the railway line was opened in order to supply this market. Arkell's (1945, p. 340) reference to 'the sand pit at South Cave (adjoining the Drewton railway-cutting)' seems to be the first published reference to the quarry. Extensive quarrying of the Kellaways Sand Member enlarged and deepened the site, but the presence of the railway line obviously restricted its expansion in a south-easterly direction. The closure of the line in 1959 enabled further sand extraction to take place and, once the track had been removed, it became possible to deepen the section described by Keeping & Middlemiss (1883). Further quarrying has caused the section previously described as Drewton Cutting to become part of the main quarry, and the entire location is therefore referred to herein as South Cave Station Quarry. The removal of sand from the quarry has practically ceased in recent years; many of the faces are now overgrown and large ponds have developed.

The Oxford Clay Formation crops out on the southern side of the former railway cutting, at the top of the quarry faces. Temporary exposures in the grass-covered slope at the top of the quarry have been produced by slippage of the Oxford

Substages	Zones	Subzones	Lithostratigraphy: Midlands		Lithostratigraphy: South Cave Station Quarry
Lower Oxfordian	Cordatum	Cordatum	Oxford Clay Formation	Weymouth Member	Brantingham Fm Beds 8-10
		Costicardia			non-sequence
		Bukowskii			
	Mariae	Praecordatum			
		Scarburgense			
Upper Callovian	Lamberti	Lamberti		Stewartby Member	
		Henrici			
	Athleta	Spinosum			
		Proniae			Oxford Clay Fm Beds 4-7
		Phaeinum		Peterborough Member	Beds 2-3
Middle Callovian	Coronatum	Grossouvrei			Bed 1
		Obductum			
	Jason	Jason			non-sequence
		Medea			
Lower Callovian (part)	Calloviense	Enodatum			Kellaways Fm Cave Rock Mbr
		Calloviense	Kellaways Formation	Kellaways Sand Member	Kellaways Sand Member

Fig. 1. The Callovian–Oxfordian succession at South Cave Station Quarry compared with the standard chronostratigraphical zonation and lithostratigraphical subdivisions of the Oxford Clay Formation and uppermost Kellaways Formation in the Midlands. Based in part on Callomon (1968), Duff (1978), Page (1989), Martill & Hudson (1991) and Cox *et al.* (1992). Since the boundary between the Kellaways Formation and the Peterborough Member of the Oxford Clay Formation in the Midlands is diachronous, its position in relation to the Calloviense–Enodatum Subzonal boundary has been simplified.

Clay: water-saturated clay from this area slumps onto the quarry floor, often forming mudflows during wet winters.

The site was designated the type locality for the *Sigaloceras planicerclus* Subzone by Callomon (1955, p. 258) [now Enodatum Subzone (Callomon 1964, pp. 276–277)] and it has been recognized as a Site of Special Scientific Interest on account of its unique geology and nationally important amphibian populations. This site and the nearby Kettlethorpe Quarry feature in the recent Geological Conservation Review publication as the 'Drewton Lane Pits' (Page & Cox 2002, pp. 309–312). Permission to visit South Cave Station Quarry should be obtained from the landowner. English Nature (now Natural England), the organization with responsibility for Sites of Special Scientific Interest, has stressed that there should be no indiscriminate hammering of or collecting from the exposures.

Data from temporary exposures and excavations at [SE 9205 3284] have been used to construct a composite section through the Oxford Clay Formation at South Cave Station Quarry (Table 1, Fig. 3).

2. HISTORY OF RESEARCH

The Oxford Clay at South Cave has received little attention since Keeping & Middlemiss (1883, p. 218) first reported its presence. From the eastern half of the railway cutting, these authors described an exposure of dark, homogeneous clay, about 15 ft [c. 4.6 m] thick. They reported that fossils were rare, but that belemnites (*Belemnites Owenii*, *B. abbreviatus*) and bivalves (*Gryphea dilatata*) were present. They considered these fossils to identify the unit as the Oxford Clay. Walton (1886, p. 16) subsequently described the Oxford Clay exposed in the cutting at Drewton as 'light' and sandy, some layers being bluish in colour and others yellow or grey.

Fox-Strangways (*in* Dakyns *et al.* 1886, p. 25) provided the first indication of ammonites in the Oxford Clay of the South Cave area, reporting '*Ammonites Comptoni*' and '*Ammonites Elizabethae*' in addition to belemnites and bivalves, and he later used these records and the original observations by Keeping & Middlemiss (1883) in his memoir on the Jurassic rocks of Yorkshire (Fox-Strangways 1892, pp. 290, 299). Unfortunately, the repository of the ammonite specimens is not mentioned in the catalogue of fossils in the latter

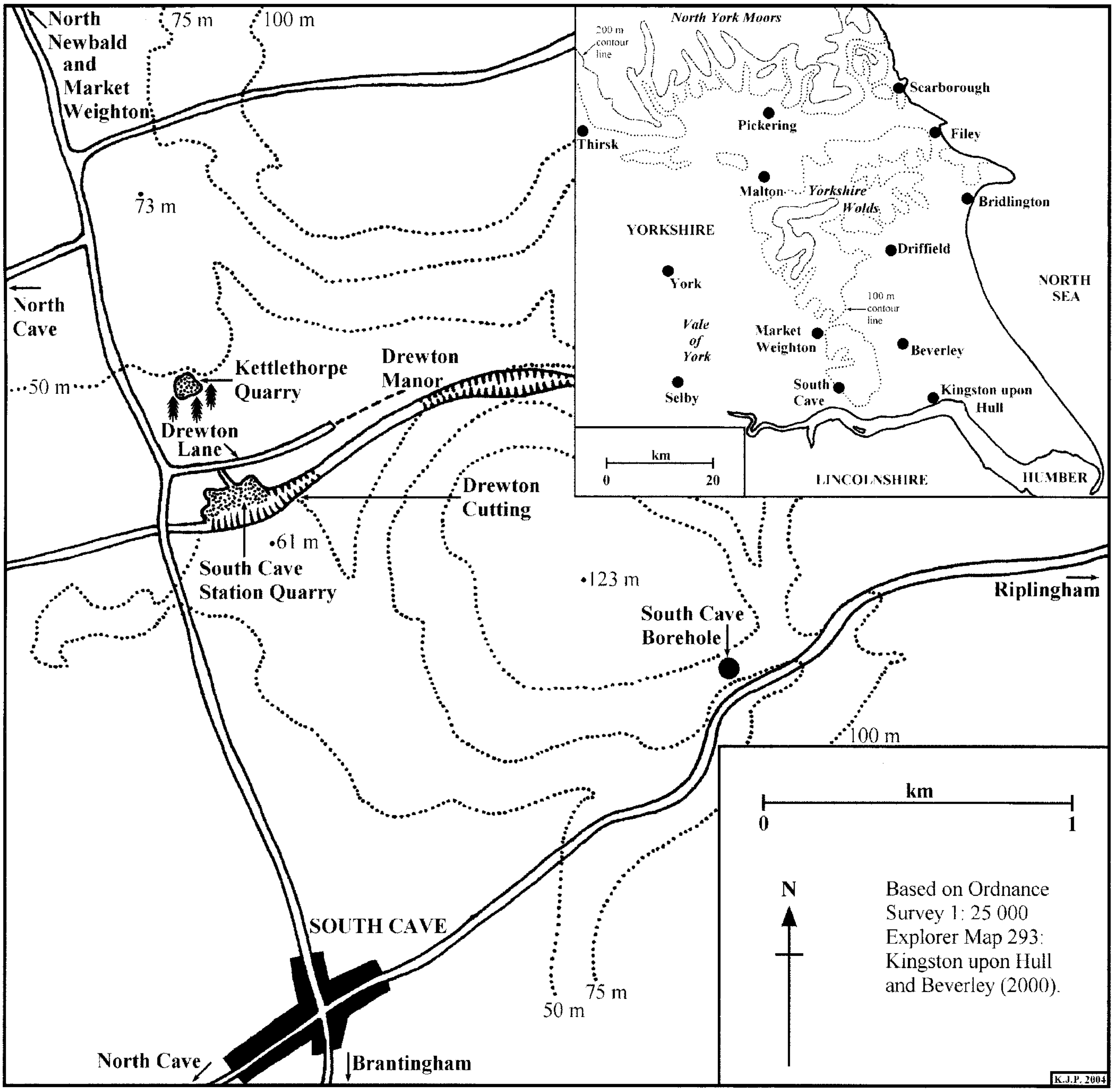

Fig. 2. The location of South Cave Station Quarry, reproduced by kind permission of the Ordnance Survey © Crown Copyright NC/04/27104.

publication (Fox-Strangways 1892, Volume II, pp. 238–239) and, despite extensive searches of the collections held at the Hull and East Riding Museum, the Yorkshire Museum and the British Geological Survey, Keyworth, they have not been located. The ammonites from the Oxford Clay at Drewton were mentioned in Arkell's classic work (1933, p. 358) on the Jurassic System in Great Britain, but not in a later paper (Arkell 1945) on the Upper Jurassic ammonite zones of Yorkshire. Since he had examined the ammonite collections held by museums at York, Scarborough, Hull and Whitby (Arkell 1945, p. 339) between 1937 and 1939, the presence of the South Cave ammonites in any of these institutions seems highly unlikely.

A further reference to ammonites from the Oxford Clay at South Cave appeared in a brief report of a field meeting by Sylvester-Bradley (1947, p. 170), who noted impressions of *Kosmoceras* spp. 'from a recently made dump of the Oxford Clay'. In subsequent papers, Neale (1958, pp. 168–169) provided a succinct description of the microfossils from the 'Upper Jurassic Clays' in the South Cave Station Quarry–Drewton area, and Walker (1972, p. 116) described the section in the railway cutting at Drewton. Walker's (1972) account was based on that of Keeping & Middlemiss (1883), with additional information from Fox-Strangways (1892). He described the Oxford Clay as bluish-grey, becoming paler towards the top of the section and very sandy and selenitic towards the base, with a thickness (seen) of 2.4 to 3 m. It seems that Walker (1972) included additional observations, as the

Table 1
Composite section through the Oxford Clay and Brantingham formations at South Cave Station Quarry

	Thickness (m)	Height of base above the Kellaways Formation (m)
Soil and vegetation		
Brantingham Formation		
Bed 10 (Cordatum Zone; Cordatum Subzone) Clay, khaki-coloured, silty in parts, disturbed by plant root activity and frost action. Rare ammonites occur as moulds-and-casts on bedding surfaces; gastropods are poorly preserved internal moulds. Sharp and planar base.	0.23	6.27
Bed 9 (Cordatum Zone; Subzone uncertain) Siltstone, cream-grey, well-consolidated, forming prominent feature due to differential weathering. Bivalves, belemnites, ammonites, crustaceans and plant remains. Fossils scattered throughout the deposit but sometimes concentrated. Structures which were originally aragonitic are preserved in silt as moulds-and-casts. Sharp and planar base.	0.25	6.02
Bed 8 (Cordatum Zone?) Silty clay, khaki-coloured with grey and orange mottles. Colour variable; grey coloration increases with depth. Locally well cemented to form discontinuous siltstones. Rare bivalves and belemnite guards; phosphatic fragments present. Sharp but irregular base; patches of grey clay incorporated within silty clay.	0.45	5.57
Oxford Clay Formation (Stewartby Member)		
Bed 7 (Athleta Zone; Proniae Subzone) Clay, plastic, colour ranges from khaki at top to grey at base. Fossils relatively common; limonite-coated pyritic ammonite nuclei and brachiopods; belemnite guards, serpulid worms and crustaceans; aragonitic bivalves preserved as clay moulds. Ammonites are especially common at a level approximately 0.25–0.30 m below the upper surface. Sharp planar base.	0.65	4.92
Bed 6 (Athleta Zone; Proniae Subzone) *Bed 6c.* Silty clay-siltstone, khaki-coloured with blocky fracture; iron-staining common along fracture lines. Fossils rare and poorly preserved. *Bed 6b.* Siltstone, pale grey, well-consolidated. Belemnites and poorly preserved bivalves. Angular to sub-rounded phosphatic fragments; 2 to 20 mm in diameter, many bored and with small serpulid worm tubes. *Bed 6a.* Siltstone, dark grey, poorly consolidated. Fossils include rare ammonites; gastropods, bivalves, fish teeth and pyritic burrows; phosphatic fragments. Sharp and planar base.	1.02†	3.90
Bed 5 (Athleta Zone; Proniae Subzone) Clay, cream-grey and interbedded with layers of dark grey silt. Serpulid worms and calcitic bivalve remains common.	0.05	3.85
Bed 4 (Athleta Zone; Proniae Subzone) Clay, blue-grey, plastic with blocky fracture. Colour varies from brown-grey close to ground surface to blue-grey at depth. Pyritized ammonites and gastropods; bivalves preserved in pyrite and as clay moulds; belemnite guards, serpulids, crinoids, crustaceans and pyritic burrows. Simple burrows with a diameter of 0.5 mm evident under the microscope. Limonite coatings are absent from pyritized fossils. Gradational, indistinct base.	2.40	1.45
Oxford Clay Formation (Peterborough Member)		
Bed 3 (Athleta Zone; ?Phaeinum Subzone) Clay-mudstone, grey with blocky fracture, increasingly consolidated towards base. Iron-staining common along fracture lines. Serpulid worms, cylindroteuthid belemnites especially common towards base, poorly preserved clay mould of an ammonite and selenite-coated remains of bivalves. Sharp base.	0.85	0.60
Bed 2 (Athleta Zone; ?Phaeinum Subzone) Clay, orange-brown, iron mineralization along bedding surfaces. Small iron nodules (typically 25 × 20 mm) scattered throughout the clay; vertical burrows (10 mm diameter) with sandy infillings at base of bed; calcitic bivalves and cylindroteuthid belemnite guards; fossil wood locally abundant. Sharp base.	0.45	0.15
Bed 1 (Coronatum Zone; Subzone uncertain) Sandy clay-clayey sandstone, cream-brown. Degree of consolidation varies; upper surface is iron-rich and very resistant. Severely corroded remains of calcitic bivalves and cylindroteuthid belemnite guards. Rare crushed fragments of poorly preserved kosmoceratid ammonite. Sharp planar base.	0.15	0.00
Total thickness of Oxford Clay and Brantingham formations	6.50	
Kellaways Formation (Cave Rock Member) (Calloviense Zone; Enodatum Subzone) Sandstone, calcite-cemented. Cylindroteuthid belemnite guards and fossil wood on upper surface.	Base not seen at this locality	

† Since coloration is influenced by weathering processes, these siltstones can appear to change in thickness from one section to another. The composite thickness value stated here is based on lithology rather than colour.

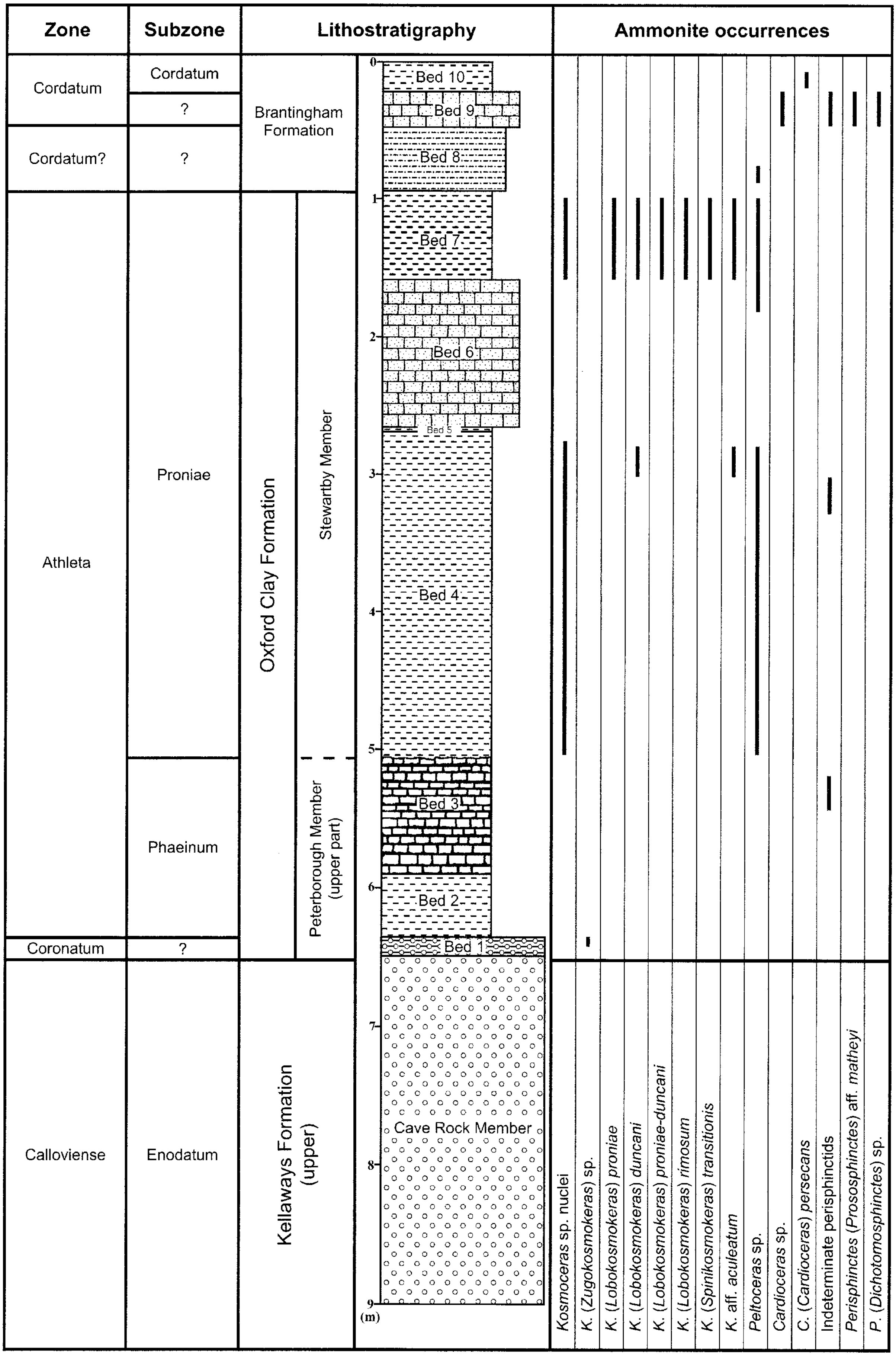

Fig. 3. Composite section showing the distribution of ammonites in the Oxford Clay and Brantingham formations at South Cave Station Quarry.

sources cited make no reference to selenite or the sandy nature of parts of the clay.

Irrespective of their whereabouts, the ammonites recorded by Fox-Strangways (*in* Dakyns *et al.* 1886) led Arkell (1933) to conclude that the Oxford Clay exposed in the South Cave area 'would seem still to belong to the *jason* zone'. The '*jason* zone' age was repeated by Neale (1958) and Walker (1972, table 1), the latter placing the Oxford Clay of East Yorkshire in the '*Kosmoceras* (*Gulielmites*) *jason* Subzone'. Neale (1958) also reported that the ammonites had been obtained from the lowest beds exposed in Drewton cutting during the construction of the railway in 1881. Cope *et al.* (1980, p. 56), however, re-evaluated this interpretation of age, and suggested that a modern assessment of the ammonites would indicate the Coronatum Zone.

In a wider context, a series of boreholes drilled in the Humber region during 1971 and 1972 has provided information on the Oxford Clay Formation in East Yorkshire (Gaunt *et al.* 1980, p. 14). Gaunt *et al.* (1992, p. 62) placed the Oxford Clay in boreholes to the north of the Humber in the Athleta Zone, although this view had been qualified by Duff (*in* Cope *et al.* 1980, p. 56). Most recently, Page & Cox (2002) gave a brief modern account of the Oxford Clay in the area. Sandy, silty and calcareous strata of Oxfordian age overlying the Oxford Clay in the Humber region were named the Brantingham Formation by Gaunt *et al.* (1980). The formation is thinner and finer grained in the South Cave area. Beds 8–10 at South Cave Station Quarry are assigned to the Brantingham Formation.

3. AMMONITE FAUNAS

The preservation of ammonites from the Oxford Clay Formation at South Cave Station Quarry appears to be very similar to that at Woodham, Buckinghamshire, as described by Hudson & Palframan (1969). The inner whorls of specimens from Beds 4–7 are preserved as uncrushed pyritic internal moulds; the outer whorls are preserved in clay. A single specimen has a body chamber with lappets preserved as a crushed clay mould. Weathering of the clays usually removes all traces of the outer whorls and the nuclei are frequently covered in a thin coating of limonite. Ammonites from the Brantingham Formation are not pyritized, but occur as moulds-and-casts in the clays and siltstones. Consequently, these specimens are more readily destroyed than pyritic specimens during weathering. Although the pyritic ammonites are beautifully preserved, the absence of the outer whorls and body chambers means that they are of limited use in biometric analyses. As at Woodham, the boundary between the pyritic nucleus and the clay whorls does not correspond to the junction between the phragmocone and body-chamber. Hudson & Palframan (1969, p. 399) noted that 'two or three complete whorls of clay mould surrounded the nucleus in ammonite species that were known to have had body chambers of one whorl or less'.

Sexual dimorphism (Makowski 1962; Callomon 1963, 1981) amongst the ammonite faunas from the Oxford Clay at South Cave is not generally recognized because the vast majority are not preserved with body chambers or even complete phragmocones. Since the inner whorls of both members of a dimorphic pair are almost identical, it is commonly impossible to determine whether a particular nucleus belonged to a macroconch [M] or microconch [m]. Secondary diagnostic features, such as lappets or the modification of ribbing on the body-chamber, are usually not preserved.

The ammonites from South Cave Station Quarry will be considered in three groups, based on their stratigraphical position: a) rare, fragmentary remains from Bed 1 at the base of the sequence; b) pyritized nuclei from Beds 4–7; and c) crushed or fragmentary remains from the Brantingham Formation. Some identifications are tentative because of the incomplete nature of the remains, and such examples are not classified beyond generic level. The following notes outline the characteristic features of the species, but they are not intended to provide a detailed systematic treatment of the ammonite fauna.

The distribution of *in situ* ammonites at South Cave Station Quarry is shown in Figure 3. The 270 specimens featured in this work will be deposited at Oxford University Museum of Natural History (OUMNH). Specimen numbers prefixed by SCSQ are those used by the author; the corresponding OUMNH registration numbers are also included.

3.1. Ammonites from Bed 1

Fragmentary remains of a kosmoceratid ammonite have been recovered from the clayey sandstone at the base of the sequence (Fig. 4). The specimen appears to be preserved in iron oxides, and the growth of mammilated iron minerals has obscured the ribbing patterns on vital areas of the whorls. However, the following features may be recognized. The whorl-section is tabulate. Although the umbilical margin is not clearly visible, lateral tubercles appear to be present, separated by a smooth band. Slightly sinuous ribs originate from the lateral tubercles and run over the venter; a small tubercle develops on each rib at the ventral margin. There is no evidence of looping of the ribs at the ventral tubercles.

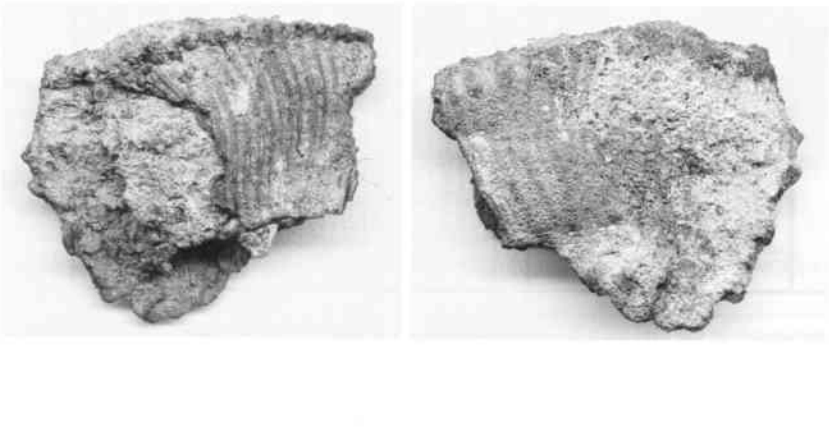

Fig. 4.
Kosmoceras (*Zugokosmokeras*) sp., Oxford Clay Formation, Peterborough Member, Bed 1, South Cave Station Quarry. KJP specimen number SCSQOxCl P3.22; Oxford University Museum of Natural History specimen number OUMNH J.69903. (× 1.5)

Although there is a close match with Page's figure (1991, pl. 15, fig. 7) of *Kosmoceras (Z.) grossouvrei*, important diagnostic features such as the size and nature of the body-chamber cannot be assessed. Therefore, the specimen is probably best described as *Kosmoceras (Zugokosmokeras)* sp.

3.2. Ammonites from Beds 4–7

The following ammonites are preserved as small, pyritic nuclei:

Kosmoceras (Lobokosmokeras) proniae Teisseyre, 1884
Many of the specimens are almost identical to the macroconch from the brick-pit at Summertown, Oxford, figured by Buckman (1923, pl. CDXXXVI). Arkell (1933, pl. XXXVII, fig. 5) illustrated the inner whorls of a macroconch. The specific diagnostic feature of *K. proniae* is the presence of a spiral smooth band that interrupts the primary ribs and produces two rows of lateral tubercles. The secondary ribs display two-fold looping, each pair joining to form a small tubercle at the ventral margin (Fig. 5.1a, b).

A specimen [SCSQOxCl 16/OUMNH J.70079] (Fig. 5.2a, b) and a whorl fragment from the slumped Oxford Clay are very similar to the examples of *Kosmoceras rowlstonense* (Young & Bird 1822) figured by Callomon & Wright (1989, p. 832, pl. 96, figs 1–4). However, positive identifications cannot be made due to the incomplete nature of the material.

Kosmoceras (Lobokosmokeras) duncani (J. Sowerby, 1817)
The macroconch and microconch forms of this species were figured by Arkell (1939, pl. XI, fig. 6 and pl. XI, fig. 7 respectively). The ribbing is fine, similar to *K. proniae*, but the secondary ribs on the inner whorls may fuse externally into groups of three or four. The ventral tubercles, or clavi, are widely spaced, giving the shell a characteristic outline (Fig. 5.3a, b).

Some specimens (Fig. 5.4a, b) from South Cave Station Quarry appear to be intermediate between *K. proniae* and *K. duncani*. These strongly resemble examples named and figured by Krenkel (1915, pl. XXI, fig. 7, figs 12–14) as *Kosmoceras proniae-duncani* Krenkel, 1915. Similar passage forms linking *K. duncani* with *K. proniae* occur in material held by Oxford University Museum (Arkell 1939, p. 193).

Kosmoceras (Lobokosmokeras) rimosum (Quenstedt, 1887)
This is the microconch partner of *K. proniae* (Callomon 1963, p. 35; figured by Callomon & Wright 1989, pl. 95, figs 3–5). The two-fold secondary ribs, with small ventral tubercles are characteristic (Figs 5.5a, b, 5.6a, b).

Kosmoceras (Spinikosmokeras) transitionis Krenkel, 1915 (*non* Nikitin)
As shown in Krenkel's figures (1915, pl. XXI, figs 20–22), some of the primary ribs of this species are interrupted by large, prominent tubercles. The secondary ribs form bundles of three or four, and most of these end with conspicuous ventral tubercles (Fig. 5.7a, b).

Kosmoceras aff. *aculeatum* (Eichwald, 1830)
Very coarsely ribbed microconch forms (Fig. 5.8a, b) resembling *Kosmoceras ornatum*, as illustrated by Krenkel (1915, pl. XX, fig. 13) and Douvillé (1915, pl. XXI, fig. 6), occur at South Cave Station Quarry in Beds 4 and 7. However, the use of *K. ornatum* for such forms is inappropriate as the name of this species needs redefining (J. H. Callomon, pers. comm., 2001). The specimens from South Cave display looped secondary ribbing, which is characteristic of *Kosmoceras* species from the Athleta Zone, and are best assigned to the reliably named coarse microconch morphospecies *Kosmoceras aculeatum* (J. H. Callomon, pers. comm., 2001).

It is possible that some of the small pyritic nuclei could be the inner whorls of *Kosmoceras (Hoplikosmokeras) gemmatum* (Phillips 1829). This species is the macroconch partner of *K. transitionis* Krenkel *non* Nikitin (Callomon 1963, p. 53); a neotype was figured by Arkell (1939, p. 189, fig. 4).

Kosmoceras (Kosmoceras) tidmoorense Arkell, 1939
Specimens resembling this species have been recovered from slumped deposits of Oxford Clay at South Cave Station Quarry (Fig. 5.9a, b). They show the features that Arkell (1939, text-fig. 3, p. 189; pl. XI, fig. 2) used to characterize the species. Numerous lateral tubercles interrupt almost all ribs and the primary ribs are double-looped.

Small, pyritized, spinose kosmoceratid nuclei from the Stewartby Member are generally assigned to *Kosmoceras spinosum*, and this name could be applied to the specimens identified herein as *Kosmoceras* aff. *aculeatum* and *Kosmoceras tidmoorense*. However, the type horizon of *Kosmoceras spinosum* lies in the Lamberti Zone and Subzone (Callomon & Cope 1995, p. 80) and the species does not seem to occur with species such as *K. proniae* and *K. duncani* (Callomon 1968, p. 275). However, as many of the specimens from South Cave are small nuclei, identification to specific level is often difficult. Since the inner whorls of many species of *Kosmoceras* display features that are different from those found on the body-chambers, very small nuclei have been identified herein as *Kosmoceras* sp.

Longaeviceras cf. *placenta* (Leckenby, 1859)
The genus *Longaeviceras* is present as two fragmentary nuclei and an incomplete whorl from slumped Oxford Clay at the base of the quarry (Figs 6.1–6.3). The nuclei closely match the septate nucleus from the Hackness Rock Member (Athleta Zone, Proniae Subzone) figured by Callomon & Wright (1989, pl. 93, fig. 4). Species of *Longaeviceras* appear to be rare elements of the fauna at South Cave.

Peltoceras sp.
Several small, pyritic nuclei have been recorded from the Oxford Clay Formation at South Cave Station Quarry, but as the inner whorls of almost all *Peltoceras* are indistinguishable (J. H. Callomon, pers. comm., 2000), they have not been described beyond generic level. Some specimens [e.g. SCSQOxCl 70/OUMNH J.70133] (Fig. 6.4a, b) are similar to Prieser's illustrations of *Parapeltoceras broilii* (Prieser 1937, pl. IV, fig. 1) and the inner whorls of *P. broilii* var. *aculeatum* (Prieser 1937, pl. IV, fig. 2), whereas others [e.g. SCSQOxCl 69/OUMNH J.70132] (Figure 6.5a, b) match the nucleus of *Parapeltoceras pseudocaprinum* Prieser, 1937 (pl. I, fig. 15; pl. II, fig. 5). It is likely that many of the pyritic *Peltoceras* nuclei found in Bed 7 are the species *Peltoceras trifidum* (Quenstedt) (J. H. Callomon, pers. comm., 2001).

Alligaticeras (Alligaticeras) rotifer (Brown, 1849)
A single specimen from the slumped Oxford Clay (Fig. 6.6a–c) displays the characteristic features of the species: bifurcate ribbing with deep, strong constrictions, moderately depressed whorl-section and a broad venter over which the ribs pass without interruption (Cox 1988, pp. 49–52; pl. 22, fig. 4).

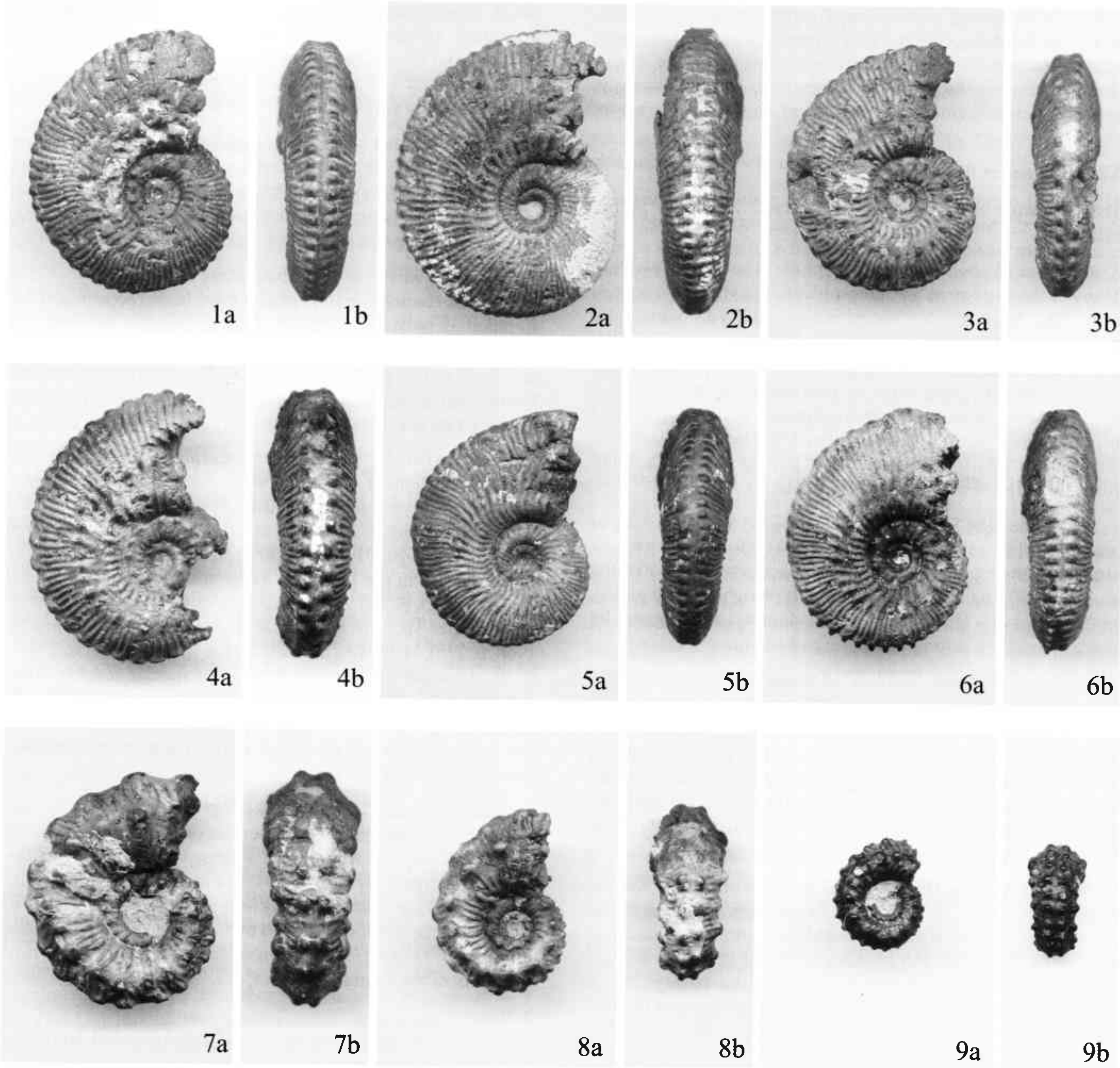

Fig. 5. Ammonites from slumped Oxford Clay Formation (Stewartby Member), South Cave Station Quarry. KJP collection specimen numbers, prefixed SCSQ, and the corresponding Oxford University (OUMNH) registration numbers are shown. (All specimens × 1.5)
5.1a, b. *Kosmoceras* (*Lobokosmokeras*) *proniae* Teisseyre, 1884. SCSQOxCl 71/OUMNH J.70134.
5.2a, b. *Kosmoceras* (*Lobokosmokeras*) *proniae* Teisseyre, 1884. SCSQOxCl 16/OUMNH J.70079. Similar to *Kosmoceras rowlstonense* (Young and Bird, 1822).
5.3a, b. *Kosmoceras* (*Lobokosmokeras*) *duncani* (J. Sowerby, 1817) [m]. SCSQOxCl 63/OUMNH J.70126.
5.4a, b. *Kosmoceras proniae-duncani* Krenkel, 1915. SCSQOxCl 89/OUMNH J.70152.
5.5a, b. *Kosmoceras* (*Lobokosmokeras*) *rimosum* (Quenstedt, 1887). SCSQOxCl 105/OUMNH J.70168.
5.6a, b. *Kosmoceras* (*Lobokosmokeras*) *rimosum* (Quenstedt, 1887). SCSQOxCl 12/OUMNH J.70075.
5.7a, b. *Kosmoceras* (*Spinikosmokeras*) *transitionis* Krenkel, 1915. SCSQOxCl 53/OUMNH J.70116.
5.8a, b. *Kosmoceras* aff. *aculeatum* (Eichwald, 1830) [m]. SCSQOxCl 81/OUMNH J.70144.
5.9a, b. *Kosmoceras* (*Kosmoceras*) *tidmoorense* Arkell, 1939. SCSQOxCl 41/OUMNH J.70104.

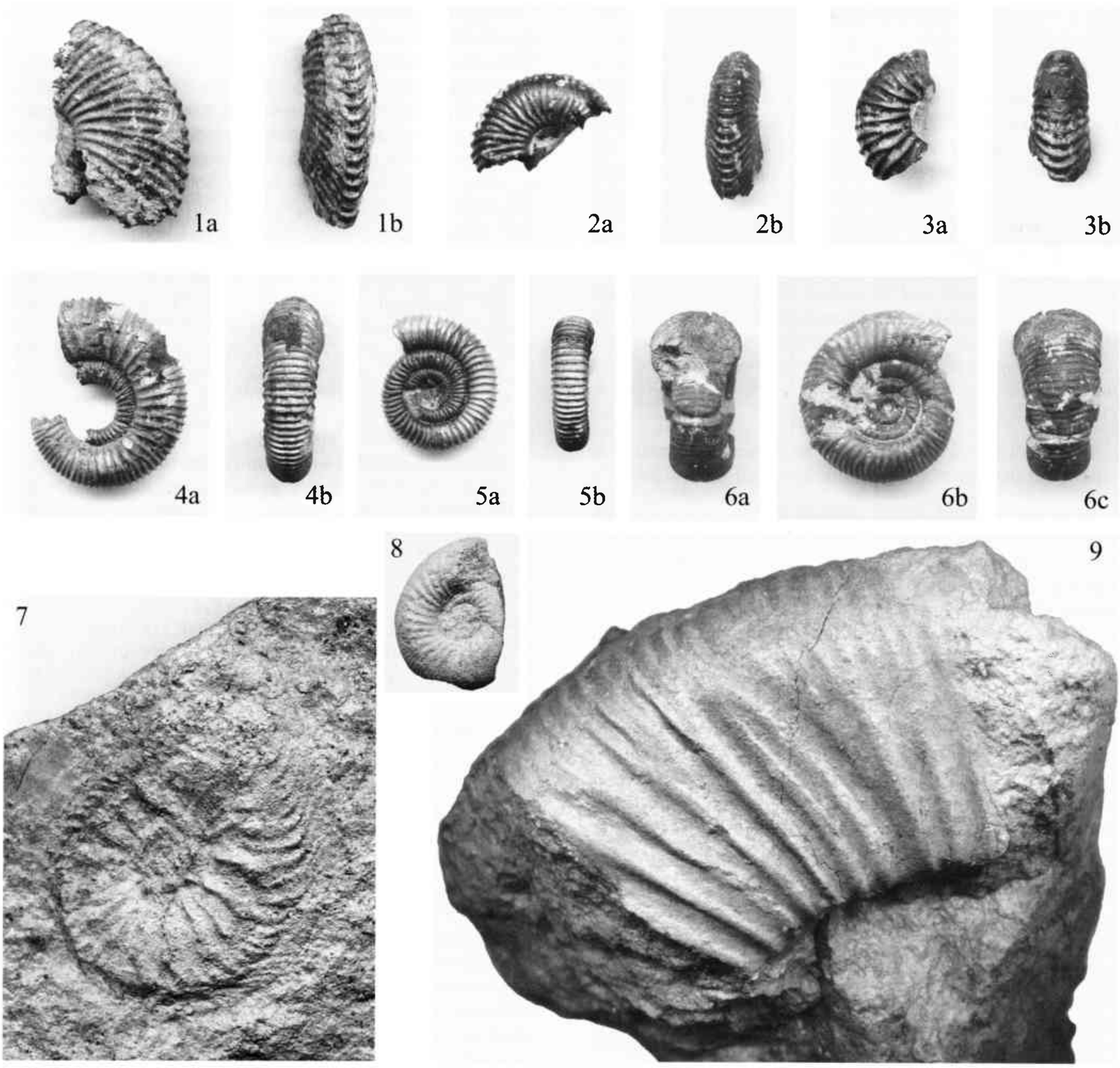

Fig. 6. Ammonites from the Oxford Clay (Stewartby Member) and Brantingham formations at South Cave Station Quarry. KJP collection specimen numbers, prefixed SCSQ, and the corresponding Oxford University (OUMNH) registration numbers are shown. (All specimens × 1.5)

6.1a, b. *Longaeviceras* sp. SCSQOxCl 27/OUMNH J.70090.
6.2a, b. *Longaeviceras* cf. *placenta* (Leckenby, 1859). SCSQOxCl 82/OUMNH J.70145.
6.3a, b. *Longaeviceras* sp. SCSQOxCl 124/OUMNH J.70187.
6.4a, b. *Peltoceras* sp. [*Parapeltoceras broilii* Prieser, 1938.] SCSQOxCl 70/OUMNH J.70133.
6.5a, b. *Peltoceras* sp. [*Parapeltoceras pseudocaprinum* Prieser, 1938.] SCSQOxCl 69/OUMNH J.70132.
6.6a–c. *Alligaticeras rotifer* (Brown, 1849). SCSQOxCl 5/OUMNH J.70068.
6.7. *Cardioceras* (*Cardioceras*) *persecans* (S. Buckman, 1925). Brantingham Formation Bed 10. SCSQBrFm 1/OUMNH J.70222.
6.8. *Perisphinctes* (*Prososphinctes*) *matheyi* de Loriol, 1898. Brantingham Formation Bed 9. SCSQBrFm 3/OUMNH J.70224.
6.9. *Perisphinctes* (*Dichotomosphinctes*) sp. Brantingham Formation Bed 9. SCSQBrFm 2/OUMNH J.70223.

3.3. Ammonites from the Brantingham Formation

3.3.1. Cardioceratids

A single specimen of *Cardioceras* (*Cardioceras*) *persecans* (S. Buckman 1925) has been collected from Bed 10 (Fig. 6.7). It is preserved as a crushed mould-and-cast in silty clay. The original shell material is absent. *Cardioceras* (*C.*) *persecans* is similar to *C.* (*C.*) *cordatum* J. Sowerby, 1813, but has ribs that are more delicate, less sharp and less tuberculate. The shoulders are less square and the keel is blunter (Arkell 1946, Part XI, p. 316; pl. LXVIII, figs 10–12; pl. LXIX, figs 4–6). Details of the keel and shoulders cannot be seen on the Brantingham Formation specimen due to its crushed state, but the ribbing pattern matches Arkell's (1946) description. The South Cave specimen is very similar to a microconch of *C.* (*C.*) *persecans* from the Birdsall Calcareous Grit figured by Wright (1983, pl. 22, fig. 2).

Two small nuclei of *Cardioceras* have been extracted from Bed 9, but they cannot be identified beyond generic level.

A limonite-coated, pyritic nucleus of *Kosmoceras proniae* was found in Bed 10, at the same level as the specimen of *Cardioceras* (*C.*) *persecans*. The presence of these fossils together is rather unusual. *K. proniae* is an Upper Callovian species (Proniae Subzone) whereas *C.* (*C.*) *persecans* occurs in the Lower Oxfordian (Cordatum Subzone). A possible explanation is that the specimen of *K. proniae* has been reworked into Bed 10. The mode of preservation is characteristic of Bed 7, whereas Brantingham Formation ammonites are preserved as clay or silt moulds-and-casts. The specimen was orientated at an angle to the bedding, but this does not provide conclusive proof of reworking. However, there is no evidence to indicate that the outer whorls and body-chamber were present in the clay matrix, and there has been some loss of surface detail on the ribs.

3.3.2. Perisphinctids

Perisphinctid ammonites are preserved in Bed 9 as moulds-and-casts. They are not pyritized and, as with the cardioceratids from Bed 10, are easily destroyed by weathering. No complete specimen has been discovered. The remains are generally uncrushed and are either small nuclei or fragments of large outer whorls. However, suture lines are not preserved, and the incomplete nature of the material means that dimensions and rib densities cannot be measured. Consequently, identification of the specimens must rely on whorl-shape, ribbing patterns and the presence of constrictions.

The small nuclei possess features that are seen in the subgenera *Prososphinctes* and *Properisphinctes*; fine, prorsiradiate primary ribs that bifurcate and run over the venter without interruption. Deep constrictions are seen on some specimens. The important features of both subgenera were described by Arkell (1936, part II, pp. xli-xlii; 1937, Part III, pp. l–li). The South Cave Station Quarry specimens have fewer constrictions than described species of *Properisphinctes*, and the fine, dense, prorsiradiate ribbing suggests that they are likely to belong to the subgenus *Prososphinctes* (Fig. 6.8). *Perisphinctes* (*Prososphinctes*) *matheyi* de Loriol, 1898, is very similar to the specimens from South Cave. An example with a lappet and a whole whorl of body-chamber figured by Arkell (1945, part X, pl. LXIII, fig. 5) provides a very close match.

Fragments of large whorls of perisphinctid ammonites show a compressed whorl-section, prominent primary ribs that bifurcate or in some instances trifurcate, intercalatory ribs, and deep constrictions (Fig. 6.9). These features are mentioned in Arkell's (1936, part II, pp. xlv-xlvi) description of the subgenus *Dichotomosphinctes*. *Dichotomosphinctes* is thought to be the microconch form of *Perisphinctes sensu stricto* (Wright 1996, p. 438). The specimens from South Cave resemble *Perisphinctes* (*Dichotomosphinctes*) *buckmani* Arkell, 1936, and *Perisphinctes* (*Dichotomosphinctes*) *antecedens* Salfeld, 1914. These species are similar, but *P.* (*D.*) *buckmani* is larger, more evolute and has more densely ribbed inner whorls than *P.* (*D.*) *antecedens* (Arkell 1938, Part IV, pp. 79–83). Both species were figured by Arkell (1938; *P.* (*D.*) *buckmani*: pl. XVII, figs 3, 13a–c; *P.* (*D.*) *antecedens*: pl. XIV, fig. 6; pl. XV, figs 1–6 and pl. XVI, fig. 8). However, the fragmentary nature of the Brantingham Formation specimens means that it is not possible to assign them conclusively to either species.

Although it is difficult to identify fragments of perisphinctid ammonites with a high degree of confidence, those in Bed 9 are assigned to *Perisphinctes* (*Prososphinctes*) aff. *matheyi* de Loriol, 1898, and *Perisphinctes* (*Dichotomosphinctes*) sp.

4. BIOSTRATIGRAPHY AND CHRONOSTRATIGRAPHY OF THE OXFORD CLAY AND BRANTINGHAM FORMATIONS AT SOUTH CAVE STATION QUARRY

4.1. Standard Chronostratigraphical Zones

The standard chronostratigraphical zones and subzones recognized in the Oxford Clay and Brantingham formations at South Cave Station Quarry are shown in Figure 3, together with the ranges of ammonite species recorded there. The Cave Rock Member of the Kellaways Formation belongs to the Enodatum Subzone of the Calloviense Zone (Callomon 1964, p. 277). Above that unit, the fragmentary specimen of *Kosmoceras* (*Zugokosmokeras*) sp. from Bed 1 of the Oxford Clay Formation suggests the Coronatum Zone; the subgenus *Zugokosmokeras* is characteristic of that zone, although the evidence of a single poorly preserved ammonite cannot be considered conclusive. However, a similar bed in the BGS Alandale, Low Field Lane and South Cave boreholes yielded *Erymnoceras*, *Kosmoceras* (*Kosmoceras*) and a perisphinctid form approaching *Peltoceras* (B. M. Cox, pers. comm., 1999), suggesting that it includes the Coronatum-Athleta zonal boundary (Duff *in* Cope *et al.* 1980, p. 56). It seems likely therefore that Bed 1 does correlate with the Coronatum Zone.

Ammonites have not been recovered from Bed 2, and Bed 3 has produced only a single indeterminate perisphinctid and a small nucleus. The 'ammonite plasters' that are typical of the Peterborough Member in the English Midlands are not evident; although the dissolution of the aragonitic ammonite shells could explain their absence from these beds, traces should still be evident if they had been present. The clays of the 'Lower *P. athleta* Zone' (Phaeinum Subzone) at Peterborough also lack ammonites (Callomon 1968, p. 278). However, it is possible that the specimens of '*Ammonites comptoni*' and '*Ammonites elizabethae*' reported by Fox-Strangways (1892) also came from Bed 3. *Ammonites* [*Binatisphinctes*] *comptoni* is common at the top of the Coronatum Zone and at the base of the Phaeinum Subzone of the Athleta Zone (Cox 1988, p. 46), while *A. elizabethae* [*Kosmoceras* (*Lobokosmokeras*) *phaeinum* or *acutistriatum*] is characteristic of the Phaeinum Subzone (J. K. Wright, pers. comm., 1999). Beds 2 and 3 are assigned tentatively to the Phaeinum Subzone of the Athleta Zone, a conclusion that is supported by belemnite, serpulid and ostracod evidence (see below).

Bed 4 does not contain an abundant ammonite fauna, but the specimens present are preserved as pyritic nuclei. This change from the crushed fossils associated with the Coronatum Zone and Phaeinum Subzone marks the transition from the Peterborough Member to the Stewartby Member (Callomon 1968, p. 274; Cox *et al.* 1992). The fauna from Bed 4 consists of *Kosmoceras duncani* [m], *Kosmoceras* aff. *aculeatum*, *Peltoceras* sp. and small, spinose nuclei of *Kosmoceras* sp., all of which are characteristic of the Proniae Subzone of the Athleta Zone. The exact position of the boundary between the Phaeinum and Proniae subzones at South Cave Station Quarry cannot be determined due to the lack of diagnostic ammonites in Bed 3.

Bed 5 has not yielded any ammonites, and they are rare in Bed 6. A single pyritic nucleus of *Kosmoceras* aff. *aculeatum* was collected from the lowest levels of Bed 6, and a poorly preserved mould-and-cast of *Peltoceras* sp. came from Bed 6c. Pyritized fossils are not common in these rocks and therefore the specimen of *K.* aff. *aculeatum* could have been incorporated into the siltstone by reworking from Bed 4. On the basis of the ammonite fauna, there appears to be little difference in age between Bed 6 and the blue-grey clay of Bed 4, and it seems likely that the serpulid-rich clay of Bed 5 does not mark a subzonal or zonal boundary.

Bed 7 contains pyritic nuclei of species that are characteristic of the Proniae Subzone: *Kosmoceras proniae*, *K. duncani* [M], *K. rimosum*, *K. transitionis*, *K.* aff. *aculeatum*, *Kosmoceras* sp. and *Peltoceras* sp.. Although ammonites are not abundant, they are more common than in any of the other beds.

Ammonite faunal horizons, as defined by Callomon (1985, 1995), can be recognized within the Proniae Subzone deposits at South Cave Station Quarry, with a lower horizon in Bed 4 and a higher horizon in Bed 7 (Fig. 7). The lower horizon is characterized by *Kosmoceras duncani* [m], *K.* aff. *aculeatum* and *Peltoceras* sp.; the fauna from the higher horizon is dominated by *K. proniae* and *K. proniae-duncani*, with *K. duncani* [M] (rare) and other taxa (Fig. 7). The horizons may be summarized as the *Kosmoceras duncani-Kosmoceras* aff. *aculeatum* horizon (lower), and the *Kosmoceras proniae* and variants-*Peltoceras* sp. horizon (higher). The *K. proniae-Peltoceras* sp. horizon is probably equivalent to the '*proniae-trifidum* horizon' of the English Midlands (J. H. Callomon, pers. comm. 2001). Further research on the biohorizons of the Athleta Zone in the United Kingdom is required in order to establish whether the *K. duncani-K.* aff. *aculeatum* horizon is of value for regional time-correlations.

Although these records correspond with some of Callomon's (1964, p. 280) observations regarding the Athleta Zone, there are important differences. The presence of both *Peltoceras* and *K. duncani* in Bed 4 is consistent with their simultaneous appearance in the Athleta Zone elsewhere, but at South Cave *K. proniae* does not range throughout the zone. This species has not been found in Bed 4, and the situation is reminiscent of the sequence at Wolvercote brick-pit, Oxford,

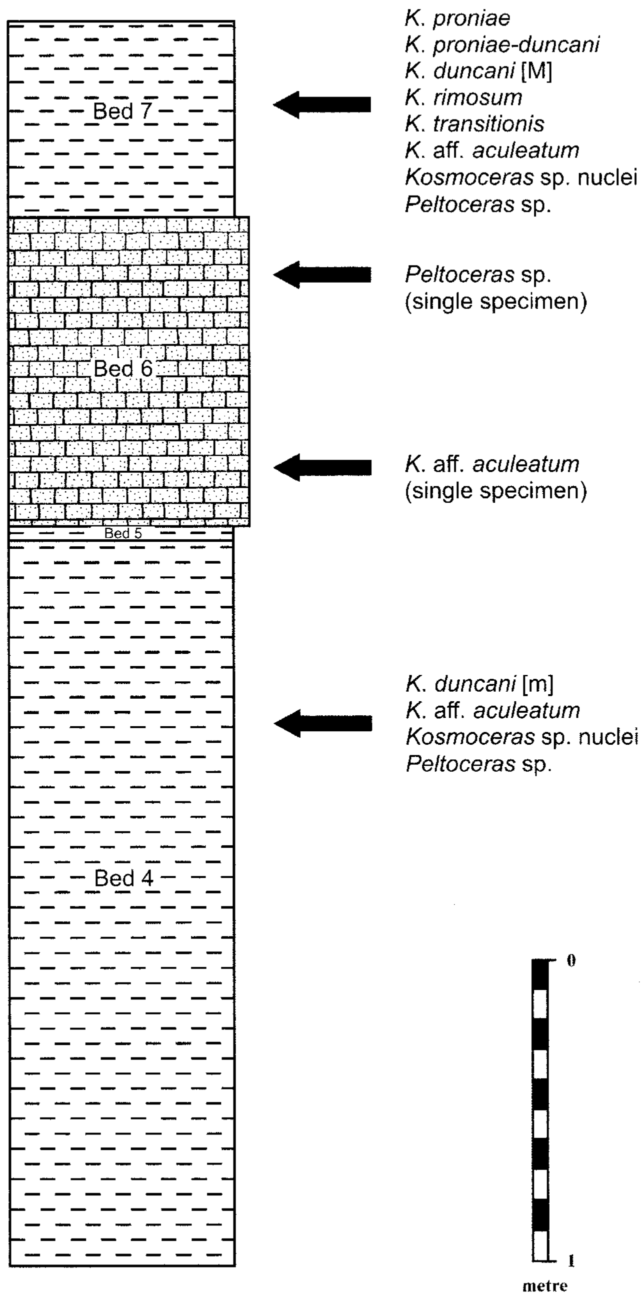

Fig. 7. Ammonite faunal horizons in the Proniae Subzone at South Cave Station Quarry.

where *K. proniae* occurred above a thin band containing *P. athleta*, whereas *K. duncani* was restricted to beds below (Arkell 1947*a*, p. 71). Arkell remarked that this pattern was not significant, and the sequence was reversed at Eye Green, Peterborough.

Two ammonites have been collected from Bed 8: an indistinct mould-and-cast of *Peltoceras* sp. and a corroded, pyritic mould of *Kosmoceras transitionis*. If these remains are autochthonous, the silty clays of Bed 8 would probably belong to the Proniae Subzone. However, the specimen of *K. transitionis*, which came from the base of this bed, is preserved in a manner that is seldom seen in this silty clay. Its stratigraphical position and style of preservation suggest that it has been reworked from an earlier deposit, most probably Bed 7. In contrast, the preservation of the *Peltoceras* is typical of the lowest beds of the Brantingham Formation. The age of Bed 8 is difficult to determine if *K. transitionis* is accepted as a reworked fossil. Forms similar to the *Peltoceras* sp. range from the Phaeinum to Spinosum subzones, and peltoceratids occur in the Lower Oxfordian (Page 1991).

Bed 9 yielded specimens of *Cardioceras* sp., *Perisphinctes* (*Prososphinctes*) aff. *matheyi* and *Perisphinctes* (*Dichotomosphinctes*) sp.. The presence of *Cardioceras* indicates an Oxfordian age, but the nuclei are too small and poorly preserved to be identified more precisely, and the zone cannot be established.

A single specimen of *Cardioceras* (*C.*) *persecans* from Bed 10 suggests the Cordatum Subzone of the Cordatum Zone (J. K. Wright, pers. comm. 1999). The base of the Cordatum Subzone is difficult to locate due to the lack of evidence from Bed 9. Evidence from BGS boreholes (Gaunt *et al.* 1980, pp. 14–15) indicates that the Brantingham Formation lies within the Cordatum and Densiplicatum zones, and therefore beds 8 and 9 at this location probably also belong to the Cordatum Zone.

4.2. Biostratigraphical evidence from other macrofossil groups and microfossils

Although ammonites provide the indices for the standard chronostratigraphical zones and subzones at South Cave Station Quarry, other macrofossils and microfossils have been recorded, and provide additional or corroborative evidence. These include belemnites, serpulid worms, foraminifera and ostracods.

Two species of belemnite can be used as guide-fossils in the Oxford Clay Formation. *Hibolithes hastata* is common in the Stewartby and Weymouth members, whereas *Cylindroteuthis puzosiana* occurs in the Peterborough Member and the Kellaways Formation (Callomon 1968, p. 269; Horton *et al.* 1995). The belemnites at South Cave Station Quarry form two distinct zones. *H. hastata* ranges from Bed 7 down to Bed 3, and *C. puzosiana* occurs in strata from Bed 3 down to Bed 1. Both species occur in Bed 3, but *Cylindroteuthis* dominates, especially at lower levels. These findings suggest that Bed 3 is part of the Peterborough Member and lies within the Phaeinum Subzone or Coronatum Zone, and corroborate the ammonite-based correlation of Bed 4 with the Stewartby Member and the Proniae Subzone.

The serpulid worm *Genicularia vertebralis* is characteristic of the Peterborough and basal Stewartby members of the Oxford Clay Formation (Horton *et al.* 1995). It is most abundant in the basal Athleta Zone (Martill *et al.* 1994, p. 178), but has been recorded from beds belonging to the 'Middle *P. athleta* Zone' (Proniae Subzone) at Milton Keynes (Horton *et al.* 1974, p. 31, fig. 11). The species ranges from Bed 3 to Bed 5 at South Cave, and is most common in Bed 3. This distribution pattern also suggests that Bed 3 probably lies in the Phaeinum Subzone, and that Bed 4 lies within the lower part of the Proniae Subzone.

Foraminifera recorded from beds 2–7 of the Oxford Clay Formation at South Cave Station Quarry include species that are indicative of the Athleta Zone, such as *Ammobaculites coprolithiformis* (Schwager, 1867), *Citharinella* sp. A Coleman, 1974, and various species of *Lenticulina.* Since species collected from the Oxfordian Brantingham Formation at this site, including *A. coprolithiformis*, *Citharina flabellata* (Guembel, 1862) and *Lenticulina subalata* (Reuss, 1854), also occur in the upper parts of the Oxford Clay Formation, their presence gives little useful information regarding the zonation of these beds. Ostracods characteristic of the Athleta Zone (the *Lophocythere interrupta sensu stricto* Ostracod Zone) have also been collected from beds 2–7. The ostracod *Neurocythere caesa caesa* (Triebel, 1951) [ex *Lophocythere*; Whatley & Ballent 2004], a subspecies that is indicative of the Athleta Zone, occurs in Bed 2 and helps to constrain the age of that bed. Samples from the Brantingham Formation did not contain ostracods.

5. CORRELATION WITH OTHER AREAS IN ENGLAND

5.1. Oxford Clay Formation (Stewartby Member)

5.1.1. Yorkshire

Kosmoceras has been recorded from the middle of the Oxford Clay Formation sequence in BGS boreholes in the area around South Cave Station Quarry. The South Cave Borehole [SE 9366 3230] yielded two specimens of *Kosmoceras* (*Spinikosmokeras*), and the East Clough Borehole [SE 9757 2490] produced single specimens of *K.* (*Spinikosmokeras*), *Kosmoceras*? and *K.* (*Lobokosmokeras*) cf. *duncani* (Gaunt *et al.* 1980, fig. 7). These findings indicate the Athleta Zone (Gaunt *et al.* 1992, p. 62), although subzones have not been recognized.

The Proniae Subzone deposits at South Cave correlate in broad terms with the Hackness Rock Member of the Osgodby Formation on the North Yorkshire coast. Inland, the Hackness Rock at Hackness Quarry has yielded a rich Proniae Subzone ammonite fauna (Wright 1968*a*, p. 392) that has similarities with the ammonite assemblages collected from the Proniae Subzone at South Cave Station Quarry. However, differences become evident when the fauna is considered at the level of the ammonite horizon. Callomon & Wright (1989, p. 802) noted that the Hackness Rock Member appeared to span two broad horizons: an earlier horizon has *Kosmoceras gemmatum* (Phillips), *K. proniae* Teisseyre, *K. duncani* (J. Sowerby) and *P. athleta* (Phillips); a later horizon is dominated by *K. rowlstonense* (Young and Bird) with *K. rimosum* (Quenstedt) and *K. spinosum* (J. de C. Sowerby). *K. gemmatum* and *P. athleta* have not been identified at South Cave and the *K. rowlstonense–K. rimosum* horizon appears to be absent. Farther west, the Hackness Rock in the Tabular and Hambleton hills appears to belong to the Lamberti Zone, with no evidence for the Athleta Zone (Wright 1978, p. 243).

Arkell (1945, p. 344) presumed that the Hackness Rock of the Athleta Zone passed laterally into Oxford Clay, but he had no evidence to support this view. However, Wright's (1968*b*, p. 95) description of limonitic casts of *Kosmoceras* (*Lobokosmokeras*) *proniae* Teisseyre and *K.* (*L.*) aff. *duncani* (J. Sowerby) from the succession in a pit at Peckondale Hill, near Malton, indicates that the Athleta Zone is present in the Oxford Clay in southern parts of the Vale of Pickering. Bed 7 at South Cave Station Quarry displays close faunal links with the Proniae Subzone deposits at Peckondale Hill. Further evidence for a link between South Cave and the area to the south-west of Malton is provided by the BGS Brown Moor Borehole, approximately 9.5 km to the south-east of Peckondale Hill (Gaunt *et al.* 1980, p. 24). The pale grey mudstones of the Athleta Zone in the Brown Moor Borehole probably correlate, at least in part, with the clays at Peckondale Hill from which the limonitic ammonite casts came. It is evident that Bed 7 at South Cave Station Quarry correlates with the Proniae Subzone at Peckondale Hill and in the Brown Moor Borehole. Gaunt *et al.* (1980, pp. 31–32) also suggested that the deposits in the Brown Moor Borehole equate with the beds containing *Kosmoceras* in the South Cave and East Clough boreholes.

5.1.2. Lincolnshire

The ammonite horizons of the Proniae Subzone at South Cave appear to be absent from the Athleta Zone in the BGS Worlaby E Borehole (Richardson 1979, p. 9). Ammonites from the 'Middle *Peltoceras athleta* Zone' there, *Kosmoceras rimosum* (Quenstedt) and *Kosmoceras* (*Kosmoceras*) *spinosum* (J. Sowerby), are typical of the higher parts of the Proniae Subzone, close to the boundary with the Spinosum Subzone.

5.1.3. Peterborough–Milton Keynes

It is difficult to correlate the Proniae Subzone deposits of South Cave with the Oxford Clay Formation in the area around Peterborough due to a lack of detailed modern accounts of the ammonite succession. Horton (1989, p. 15) simply mentioned the presence of species of *Kosmoceras* in the Stewartby Member. Neaverson's (1925, pp. 33–34) description of the fauna at Eye Green indicates that the Proniae Subzone and possibly the Spinosum Subzone are present.

Beds that seem to be equivalent to Bed 7 at South Cave Station Quarry have been encountered in the area around Bedford. The London Brick Company's Rookery Pit North at Stewartby revealed *c.* 5 m of clay belonging to the Proniae Subzone and containing *K. proniae* and *K. rowlstonense* (J. H. Callomon, pers. comm., 2001). Callomon (MS 1969; summarized by Cox *in* Wyatt *et al.* 1988, pp. 22–24) recorded clays with *K. proniae*, *K. rimosum* and *K. duncani*, indicating the Proniae Subzone, at Millbrook, south of Stewartby.

Ammonite assemblages from the Stewartby Member south of Milton Keynes closely match the ammonite horizons at South Cave Station Quarry. Callomon (1968, p. 282) described a pyritized ammonite fauna, reminiscent of that encountered at South Cave, from Bed 21 of the London Brick Company's Newton Longville pit, south-west of Bletchley. A cutting for the diverted A5 road at Milton Keynes exposed clays of the Proniae Subzone with two distinct ammonite horizons, a higher horizon with *Peltoceras* cf. *trifidum* and *K. proniae*, and a lower one with *K. proniae*, *K. duncani* and *K.* '*spinosum*' (J. H. Callomon, pers. comm. 2001; Shephard–Thorn *et al.* 1994, p. 18).

5.1.4. Oxford and the surrounding area

There are strong faunal links between the deposits of the Proniae Subzone at South Cave and those in the Oxford area. The former brick-pit, at Wolvercote, described in detail by Arkell (1947*a*, pp. 70–71), yielded pyritized ammonites of the Proniae Subzone. The composition of the fauna, as recorded by Arkell (1939, p. 208), is similar to that from Bed 7 at South Cave, with *Kosmoceras proniae*, *K. duncani*, *K. proniae-duncani* var. α and β, *K. compressum*, *K. transitionis* Lahusen *et* Krenkel *non* Nikitin, *K. spinosum*, *K. tidmoorense*, *K. rowlstonense*. *Kosmoceras compressum*, *K. spinosum* and *K. rowlstonense* suggest that the beds at Wolvercote reached a slightly higher level than those at South Cave, probably the Spinosum Subzone. As at Milton Keynes, distinctive ammonite horizons can be recognized, with *K. proniae*, *K. proniae-duncani* and *P. trifidum* occurring above *K. duncani* (J. H. Callomon, pers. comm., 2001). This is almost identical to the sequence of ammonite horizons shown in Figure 7.

Further similarities between South Cave and Oxford are evident in the clays of the Athleta Zone, which were exposed in the base of Summertown brick-pit (Arkell 1947*a*, p. 71). No section was ever published, but Pringle (1926, pp. 32, 37) gave a list of ammonites, which suggests that the beds in the pit ranged from the Proniae Subzone to the Lamberti Zone. Callomon's studies of material held by Oxford University Museum indicate that the *proniae-trifidum* horizon seen at Wolvercote was also present at Summertown (J. H. Callomon, pers. comm., 2001). A complete succession through the Oxford Clay was encountered in site investigation boreholes for the M40 motorway near Thame, but the description of the Stewartby Member in Horton *et al.* (1995, p. 25) only mentions 'zonally diagnostic' *Kosmoceras* and *Quenstedtoceras*.

The Athleta Zone at Calvert, north-east of Bicester, also contains ammonites that are typical of the *proniae-trifidum* horizon (Callomon 1968). The dominant faunal elements are *Kosmoceras rowlstonense*, *K. proniae*, *K. proniae-duncani* var. α Krenkel, *K. duncani*, *K. bigoti* (Douvillé), *K. rimosum*, *K. transitionis* Krenkel *non* Nikitin, *K. tidmoorense* and *K.* cf. *spinosum*, *Peltoceras athleta* var. *bifidum* and *P. trifidum* (p. 285). *Peltoceras athleta*, *Kosmoceras proniae* and allies form a distinct fauna at one level, providing a close match with the upper ammonite horizon at South Cave Station Quarry. A higher faunal level at Calvert yielded *Peltoceras* sp. and *Kosmoceras* cf. *spinosum* (Callomon 1968, p. 287), suggesting the upper part of the Athleta Zone (Spinosum Subzone).

5.1.5. Dorset

Arkell (1947*b*, p. 29) originally described the section through the Athleta Zone in the Stewartby Member at Crook Hill brick-pit, south of Chickerell Church, and Callomon & Cope (1995, p. 81) provided a modern summary. The presence of *Peltoceras trifidum* and *K. proniae* suggests correlation with the Athleta Zone of the areas around Oxford and Peterborough, and therefore with Bed 7 at South Cave Station Quarry.

5.2. Brantingham Formation

5.2.1. Yorkshire

Gray (1955) recorded Oxfordian clays and arenaceous limestones in industrial boreholes around Melton, to the south of South Cave. The limestones contained spicules of the sponge *Rhaxella*, and were described by Gray (1955, p. 25) as 'Corallian Beds'. Neale (1958, p. 169) remarked that they were reminiscent of the Lower Calcareous Grit of North Yorkshire, and suggested that their absence from boreholes at Welton, a short distance to the north of Melton, indicated that, whereas shallow water conditions existed in the latter area during Oxfordian times, muddier waters were present farther north. BGS boreholes in 1971–1972 provided additional data, and the subsequent report (Gaunt *et al.* 1980, p. 14) introduced the

Brantingham Formation for sandy, silty and calcareous strata of Oxfordian age in the Humber area.

As indicated above, Bed 10 at South Cave Station Quarry belongs to the Cordatum Subzone of the Cordatum Zone. This contrasts with the situation in the South Cave Borehole, 1.7 km ESE of Station Quarry (Fig. 2), where the basal beds of the Brantingham Formation are sandstones and siltstones of the overlying Densiplicatum Zone (Gaunt *et al.* 1992, pp. 62–65). The Cordatum Zone in the Alandale Borehole, near Hessle, is dominated by sandstones, and therefore the presence of fine-grained beds at Station Quarry supports Neale's view (1958, p. 169) that depositional conditions changed from shallow to deeper water over a short distance. It seems likely that Brantingham Formation beds of the Cordatum Zone were deposited over a wide area and then removed, in parts, by erosion beneath the upper Brantingham Formation (J. K. Wright, pers. comm., 1999).

Correlation between the Brantingham Formation in East Yorkshire and deposits in adjoining areas is difficult due to rapid lateral variations in lithology. Gaunt *et al.* (1992, p. 62) considered the rocks of the Brantingham Formation encountered in BGS boreholes in the Humber area to be of local occurrence only and not to correspond to the Corallian rocks of NE Yorkshire, despite some lithological similarities. These authors also noted the lithological difference between the Brantingham Formation and the correlative West Walton Formation of the southern East Midlands, the latter largely comprising a succession of interbedded mudstone and siltstone (Gaunt *et al.* 1992, p. 65).

Rocks of the Cordatum Subzone in the Brown Moor Borehole, with *Cardioceras* (*C.*) *cordatum*, comprise the Birdsall Calcareous Grit, a sequence of fine-grained sandstones with thin limestones. In a situation similar to that at South Cave Station Quarry, the beds lie non-sequentially on the Oxford Clay Formation of the Athleta Zone (Gaunt *et al.* 1980, p. 24, fig. 12). It is thought that the lower Brantingham Formation correlates with the Birdsall Calcareous Grit on the northern side of the Market Weighton Block (J. K. Wright, pers. comm., 1999). Indeed, Gaunt *et al.* (1980, p. 32) suggested such a link, but indicated that it was not possible to establish whether the two units were originally continuous.

5.2.2. *Lincolnshire*

Although the Cordatum Zone was recognized in the Worlaby E Borehole, it was not possible to distinguish between the Costicardia and Cordatum subzones. The beds assigned to these subzones in the borehole consist of 3.05 m of calcareous siltstones with bands of hard argillaceous limestone (Richardson 1979). *Cardioceras* (*Vertebriceras*) *sp.* cf. or aff. *quadrarium* S. Buckman is present, and as this species and its allies are usually associated with the Costicardia Subzone (Page 1991, p. 120), it seems that the Cordatum Zone deposits at Worlaby cannot be correlated with the Brantingham Formation of South Cave Station Quarry. Gaunt *et al.* (1992, p. 62) noted that the Brantingham Formation is difficult to delineate south of the Humber.

5.2.3. *North Norfolk to Oxford and the surrounding area*

There are marked faunal and lithological similarities between the Oxfordian Brantingham Formation strata at South Cave Station Quarry and the beds of the West Walton Formation in the East Midlands, including similarities in preservation. Ammonites in the basal beds of the West Walton Formation are preserved as clay casts with a brown calcitic film (Gallois & Cox 1977, p. 211). This contrasts with the pyritic nuclei found in the Stewartby Member of the Oxford Clay Formation, and is reminiscent of the Brantingham Formation specimens from South Cave. Perisphinctid ammonites occur throughout the West Walton Formation, and are often fragmented or preserved as small nuclei (Gallois & Cox 1977, pp. 214–215), as is the case in Bed 9 of the Brantingham Formation. The beds of the Cordatum Subzone at West Walton (beds 2–4 of Gallois & Cox 1977, fig. 2) consist of silty mudstones overlain by pale grey, very calcareous mudstone. It seems that the siltstones and clays of the Cordatum Subzone at South Cave Station Quarry are closer lithologically to the West Walton Formation in Norfolk than to the arenaceous beds of the Brantingham Formation encountered in the Alandale Borehole. The West Walton Formation can be traced from its type area in the East Midlands to the east of Oxford, but to the west of that city the upper part of the formation is replaced by calcareous and arenaceous beds of the Corallian Formation (Horton *et al.* 1995, pp. 30–31).

6. GEOLOGICAL HISTORY

The calcareous sandstones of the Cave Rock Member (Enodatum Subzone) were deposited under shallow, subtidal conditions. In central and southern England, correlative beds comprise the lowest levels of the Oxford Clay Formation, indicating a facies change. The Jason Zone (Medea and Jason subzones) succeeds the Enodatum Subzone in southern England, but deposits of Jason Zone age are absent from South Cave Station Quarry (Fig. 1). This situation is not peculiar to South Cave. Arkell (1945, p. 344) remarked that the Jason Zone had not been recorded in Yorkshire, and Gaunt *et al.* (1980, p. 31) noted that it had not been described north of Peterborough. Fossil wood and severely corroded belemnite guards are preserved on the upper surface of the Cave Rock Member at South Cave Station Quarry, and it is possible that a period of erosion resulted in truncation of the deposits of the Enodatum Subzone.

Marine conditions existed in the South Cave area during the Coronatum Zone. Bed 1 was probably derived from reworking of the Cave Rock Member during marine transgression. The lack of diagnostic ammonites hinders attempts to establish exactly when this relative rise in sea-level occurred. The top of the Coronatum Zone in southern and central England is marked by the Comptoni Bed, a thin shell bed dominated by perisphinctid ammonites, especially *Binatisphinctes comptoni*. An equally prominent bed, the Acutistriatum Band, occurs at the base of the overlying Athleta Zone. These beds have not been recorded at South Cave Station Quarry, and it seems that the Coronatum-Athleta zonal boundary may well occur in Bed 1. If so, the non-sequence between Bed 1 and the Cave Rock Member would span the Jason Zone and much of the Coronatum Zone.

Bed 2 was deposited under normal marine conditions. Bioturbation has incorporated sand from the bed below into the lower layers of this clay, and there is no evidence of a non-sequence between these beds. Bed 3 is typical of the Peterborough Member of the Oxford Clay Formation, and similar deposits have been recorded across the East Midlands (Callomon 1968). The indistinct boundary between this bed

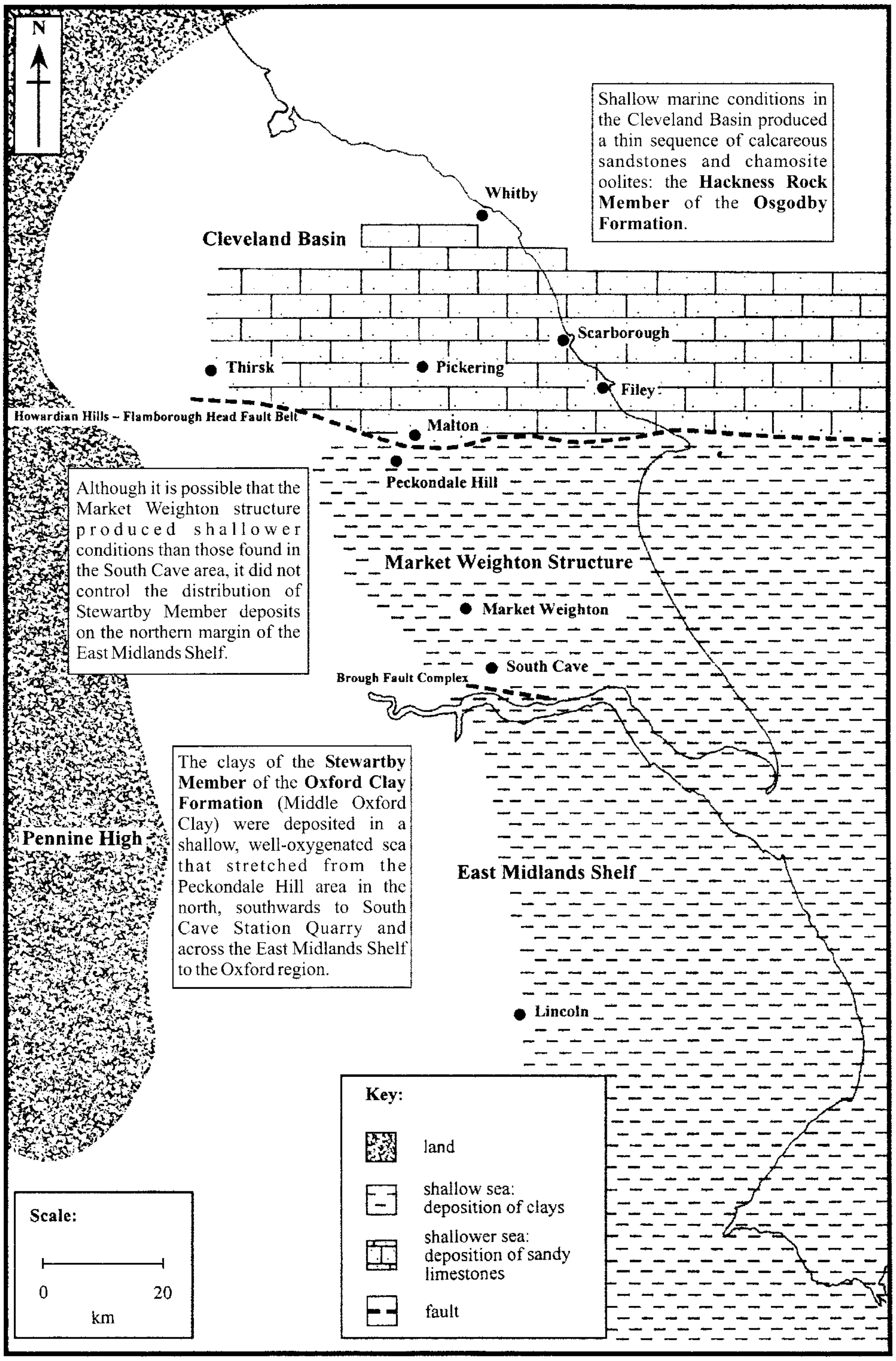

Fig. 8. Palaeogeographical reconstruction for the Yorkshire and Lincolnshire region during the Late Callovian Age (Athleta Zone, Proniae Subzone). Adapted from Bradshaw & Cripps (1992) and Rawson & Wright (1995) with additional information from the current author.

and Bed 4 marks the transition from the Phaeinum Subzone to the Proniae Subzone and the Stewartby Member. Lithologies become more calcareous and less organic-rich in the Proniae Subzone.

Deposition of the blue-grey clay of Bed 4 continued for some time, but the presence of the serpulid-rich Bed 5 suggests a period when clay deposition was limited. This also coincides with a lithological change, with the siltstones of Bed 6 replacing the underlying clays. A fall in relative sea-level seems the most likely explanation for the change. The ammonite-rich clay of Bed 7 indicates a return to deeper water conditions. The ammonite fauna of this bed displays a clear link with the Proniae Subzone of central and southern England.

Brantingham Formation rocks of the Cordatum Zone rest non-sequentially on Bed 7; the Spinosum Subzone, Lamberti and Mariae zones and the Bukowskii and Costicardia subzones are absent, probably due to erosion. This stratigraphical gap seems to be restricted to the East Yorkshire region, as these zones are present in the Cleveland Basin (Rawson & Wright 1995, p. 178, fig. 5) and Lincolnshire (Richardson 1979, p. 9). A similar non-sequence occurs at Acklam, where the Birdsall Calcareous Grit (Cordatum Zone) lies on Oxford Clay of the Athleta Zone (Gaunt *et al.*

1980, p. 24, fig. 12). Beds 8 and 9 of the Brantingham Formation suggest shallow, well-oxygenated conditions, with the clays of Bed 10 being deposited in deeper water.

In terms of regional palaeogeography, the Market Weighton Structure is now regarded as a hinge between two subsiding areas to its north and south, respectively the Cleveland Basin of North Yorkshire and the East Midlands Shelf (Gaunt *et al.* 1992, p. 30). However, although the structure had some influence on the thickness of the Jurassic strata, its influence on facies during the Late Callovian and Early Oxfordian appears to have been limited (Kent 1955, p. 211; Neale *in* discussion of Kent 1955, p. 225; Neale 1958, p. 174; Wright 1968*b*, p. 96). In Kent's (1980, p. 114) opinion, the removal of the Oxford Clay in the Market Weighton area '. . . probably dates from an early Oxfordian phase of uplift and erosion . . .'. Thus, the idea of the Market Weighton Structure separating the deposits of the East Midlands from those of the Cleveland Basin, as described by Gaunt *et al.* (1992, p. 30), may be slightly misleading. There are strong similarities between the Athleta Zone Oxford Clay sequences at Peckondale Hill and South Cave, respectively north and south of Market Weighton, both of which display closer links with the succession in the Midlands than with the deposits of the Cleveland Basin. It is possible that the Market Weighton Structure gave rise to shallow-water conditions between Acklam and South Cave. If so, this area might have been the source of the silty sediments encountered during this study.

As indicated, the succession at South Cave Station Quarry contains two major non-sequences. The lower non-sequence can be traced into Lincolnshire and North Yorkshire, and is not influenced by the Market Weighton Structure. The higher non-sequence occurs between the Stewartby Member of the Oxford Clay and the overlying Brantingham Formation, and appears to be restricted to the local area. The absence of the Weymouth Member of the Oxford Clay Formation has been linked to the presence of a series of sub-parallel faults, described as the Brough Fault Complex, in the area between Brough and North Ferriby. It is thought that movements in later Callovian to early Oxfordian times resulted in the erosion of the Kellaways Formation and the overlying mudstones (Gaunt *et al.* 1992, p. 106). A palaeogeographical reconstruction for the Yorkshire and Lincolnshire region during the Late Callovian Age (Athleta Zone) is presented in Figure 8.

7. CONCLUSIONS

The succession at South Cave Station Quarry, described historically as 'Oxford Clay', can be divided into the Callovian Oxford Clay Formation (upper part of the Peterborough Member and the Stewartby Member) and the Brantingham Formation of Oxfordian age. Ammonite assemblages enable recognition of the standard zones, with supplementary evidence from belemnites, serpulid worms, foraminifera and ostracods. The Coronatum Zone may be represented by a thin bed of clayey sandstone at the base of the Oxford Clay, which otherwise belongs to the Athleta Zone (Phaeinum and Proniae subzones). The sediments of the Brantingham Formation belong to the Cordatum Subzone of the Cordatum Zone.

Two significant non-sequences are present; the lower non-sequence can be recognized in North Yorkshire and Lincolnshire, whereas the higher appears to be restricted to the South Cave and Acklam areas. Clear faunal links are evident between Proniae Subzone strata at South Cave Station Quarry and those at Peckondale Hill and Acklam, near Malton, and at Oxford and Milton Keynes. Ammonite horizons seen at South Cave Station Quarry have been identified in the area between Oxford and Peterborough, thereby revealing strong similarities between the former and the deposits of the East Midlands Shelf.

The South Cave area was situated at the northern edge of the East Midlands Shelf. Its proximity to the Market Weighton Structure seems to have had little impact on the nature of the strata. Erosion associated with movements of the Brough Fault Complex may have been responsible for the absence of the Weymouth Member of the Oxford Clay Formation. South Cave Station Quarry provides the only location in the region where the Stewartby Member of the Oxford Clay and the beds of the Brantingham Formation may be seen at outcrop, and South Cave Station Quarry has an important role to play in the correlation of the Athleta and Cordatum Zones in the British Isles.

Acknowledgements. The author wishes to thank the curators of the collections mentioned in the text for providing information concerning the location of specimens. I am grateful to Mr P. A. Jeffrey for arranging the registration of material from the KJP collection with Oxford University Museum of Natural History. Thanks are due to Dr B. M. Cox (formerly British Geological Survey, Keyworth) for supplying data on the Kellaways Formation at South Cave. Dr J. K. Wright (Royal Holloway, University of London) is thanked for commenting on a draft version of this paper and for giving advice on lithostratigraphical matters. I am especially grateful to Prof. J. H. Callomon (University College London) for sharing his observations on the Oxford Clay deposits of the East Midlands and for providing helpful comments regarding the ammonite faunas. I am indebted to Mr R. Johnson of North Newbald for allowing access to South Cave Station Quarry. English Nature (North & East Yorkshire Team, York) kindly provided advice regarding protection of the site, and Ordnance Survey granted permission to use their data in Figure 2. Dr S. G. Molyneux (British Geological Survey, Keyworth) and the two referees, Drs B. M. Cox and K. N. Page, are thanked for their helpful comments.

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Revised manuscript received: 6th May 2005
Scientific editing by Peter Rawson