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Holocene deposits from Neptune's Cave, Nordland, Norway: Environmental interpretation and relation to the deglacial and emergence history of the Velfjord–Tosenfjord area

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Neptune's Cave in the Velfjord–Tosenfjord area of Nordland, Norway is described, together with its various organic deposits. Samples of attached barnacles, loose marine molluscs, animal bones and organic sediments were dated, with radiocarbon ages of 9840±90 and 9570±80 yr BP being derived for the barnacles and molluscs, based on the superseded but locally used marine reservoir age of 440 years. A growth temperature of *c*. 7.5°C in undiluted seawater is deduced from the $\delta^{13}C$ and $\delta^{18}O$ values of both types of marine shell, which is consistent with their early Holocene age. From the dates, and an assessment of local Holocene uplift and Weichselian deglaciation, a scenario is constructed that could explain the situation and condition of the various deposits. The analysis uses assumed local isobases and sea-level curve to give results: that are consistent with previous data, that equate the demise of the barnacles to the collapse of a tidewater glacier in Tosenfjord, and that constrain the minimum extent of local Holocene uplift. An elk fell into the cave in the mid-Holocene at 5100±70 yr BP, after which a much later single 'bog-burst' event at 1780±70 yr BP could explain the transport of the various loose deposits further into the cave.

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The value of cave deposits as recorders of palaeoenvironmental conditions is increasingly recognized (e.g. Lauritzen 1991a; Lauritzen & Lundberg 1999; Williams *et al*. 1999). In Norway, cave sediments have revealed the timing of Weichselian stadials and interstadials (e.g. Larsen *et al*. 1987; Larsen & Mangerud 1989), and speleothem dating has indicated the timing of earlier Pleistocene events (e.g. Lauritzen 1991b). Marine caves at relatively high altitudes in east Sweden and along the Norwegian coast demonstrate the extent of local glacio-isostatic and neotectonic uplift (Sjöberg 1981, 1988). Neptune's Cave provides an opportunity for dated shells and other materials from a marine-influenced karst cave in the Velfjord–Tosenfjord area of Norway to aid understanding of the local deglacial and postglacial history. Four large animal bones and many loose sea shells and barnacles attached to passage walls were observed at altitudes up to 109 m above sea level (a.s.l.) when this cave was first visited in July 1997 (Newton 1998, 1999). The first-named author returned to this rather inaccessible site on 10 July 1998 to collect samples. This article provides a permanent record of the cave's various exotic deposits and their dated ages, and considers possible explanations for their derivation. All ages refer to ^{14}C yr BP, AD 1950. A marine reservoir age of 440 yr is used when discussing marine shells, consistent with previous local moraine datings and adjacent sea-level curves.

Area and cave descriptions

Velfjord and Tosenfjord lie along the central Norwegian coast of Nordland (Fig. 1), within the Helgeland Nappe Complex of the Scandinavian Caledonides that were glaciated repeatedly during the Pleistocene. The bedrock consists of Cambro-Silurian metamorphic complexes of mica-schist, mica-gneiss, granite, diorite and metacarbonates (Gustavson 1981). Several peaks rise above 700 m a.s.l. and the area is heavily forested with pine and birch below *c*. 300 m a.s.l. Neptune's Cave lies in a folded band of marble on a steep forested hillside above the narrow lake Ursvatn, between Younger Dryas (YD) and Preboreal end moraines. It has a surveyed length of 433 m and an elevational range of 93–126 m a.s.l. (Figs 2, 3). A 6 m ladder is required to enter the dry Pot Entrance. A small tube leads from above the base of this shaft into the descending Bone Passage that connects to all other parts of the cave. The passages form a series of looping tubes, commonly 2 m wide and 3 m high, above an active series that leads to the small resurgence entrance. Most of the higher passages are dry in summer, but with damp sediments. Cockle Way ascends from the base of Bone Passage to the dry Rift Entrance. Another entrance, now blocked by infill, probably existed above Barnacle Street and Scallop Hall. Spring snowmelt likely flows down the Pot Entrance, and perhaps via the Rift Entrance and Scallop Hall, but no large streams ever flow along the passages with floor deposits, because these would be flushed from the cave.

Previous work in the area

Several local marble caves (1–10 in Fig. 1) have been described by St.Pierre & St.Pierre (1980) and Faulkner

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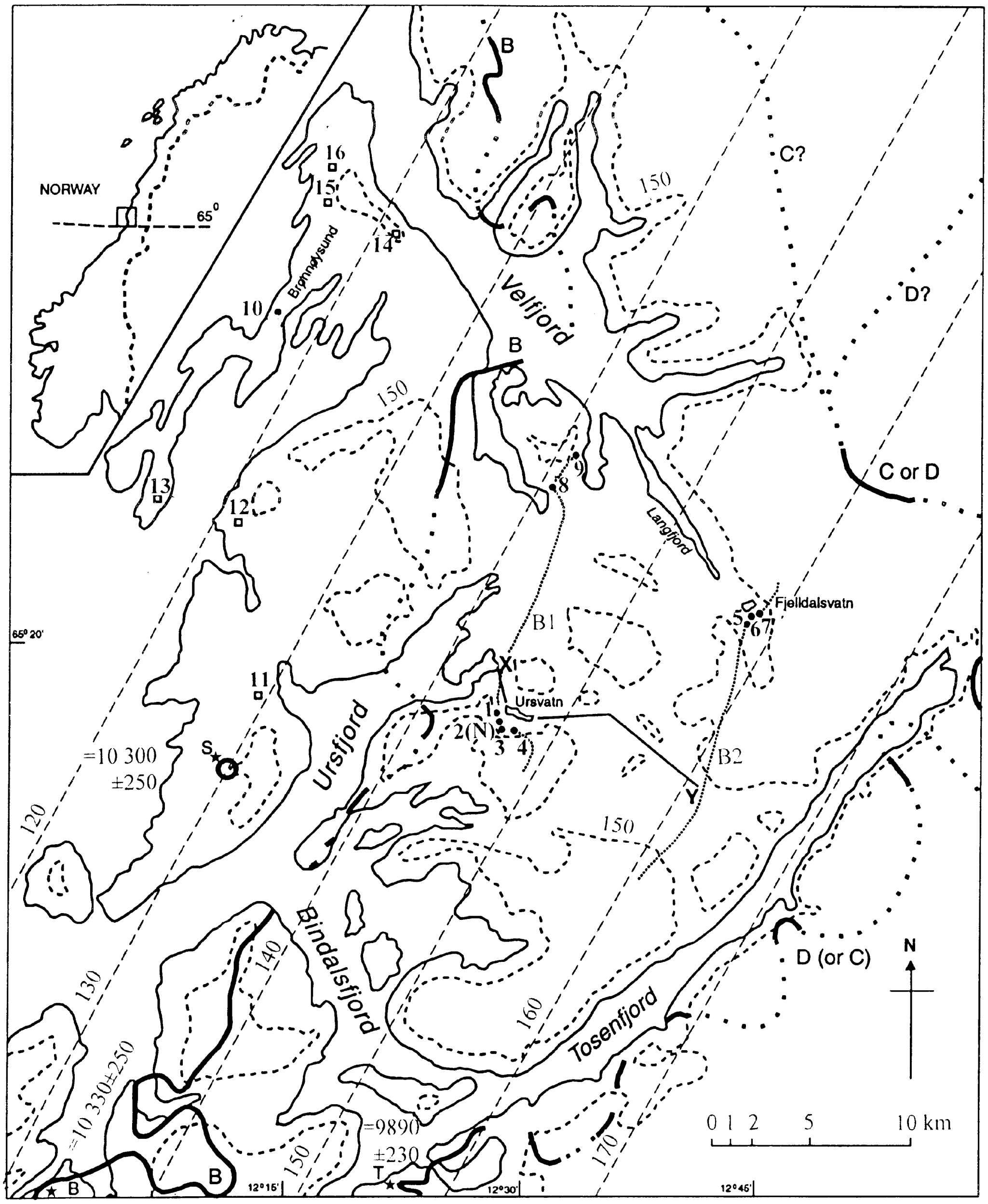

Fig. 1. Area map showing caves, marginal moraines and YD isobases (m a.s.l.). Younger Dryas isobases are extrapolated and interpolated from Sørensen *et al.* (1987). Marginal moraines, ages in ^{14}C yr BP and interpolations are according to Andersen *et al.* (1981). The 150 m contour indicates the approximate extent of marine inundation after the ice melted at the start of the Holocene. Karst caves are shown with a black dot: 1 = Svartdalgrotta; 2(N) = Neptune's Cave; 3 = Barnacle Cave; 4 = Draugenshullet; 5, 6, 7 = Aunhattenhule 1, 2, 3; 8 = Naustvik holes; 9 = Hegga Quarry Cave; 10 = Football Pitch Caves. Non-carbonate sea caves are shown with an open square: 11 = Holinhullet; 12 = Havlarsholet; 13 = Torghatt-hullet; 14 = Monshola; 15 = Tilremgrotta; 16 = Mogrotta. Marginal moraines B (Younger Dryas), C and D (Preboreal) are indicated by heavy black lines, with dated moraines at sites S* (Steindal), B* (Bogen) and T* (Terråk). Refer to text for discussion about assumed intermediate ice margins B1, B2 and the ice-margin retreat line XY.

& Newton (1995), as summarized with any reported deposits in Table 1. Hoel (1906) described three caves (5–7) with large entrances in the mountain Aunhatten that overlooks Fjelldalsvatn. They commonly reduce to 2 m wide by 2.5–3 m high after several tens of metres and partially terminate at fills of sediment (e.g. a beach formation of round stones in a clay matrix) (Hoel 1906). Hoel considered the small size of the contained shells of *Saxicava pholadis* (L.), which were commonly ≤4–5 mm long and very thin-shelled, to be significant. Noting that this species can live at depths from the beach down to 60 fathoms, and in a young condition prefer to live in deep water, he reasoned that they lived at only 4–5 m depth and did not develop in size. From their location he deduced that they must be of late-glacial age and discussed the implications for the uplift of the shoreline, making comparisons with the reporting of raised beaches and strandlines by contemporary

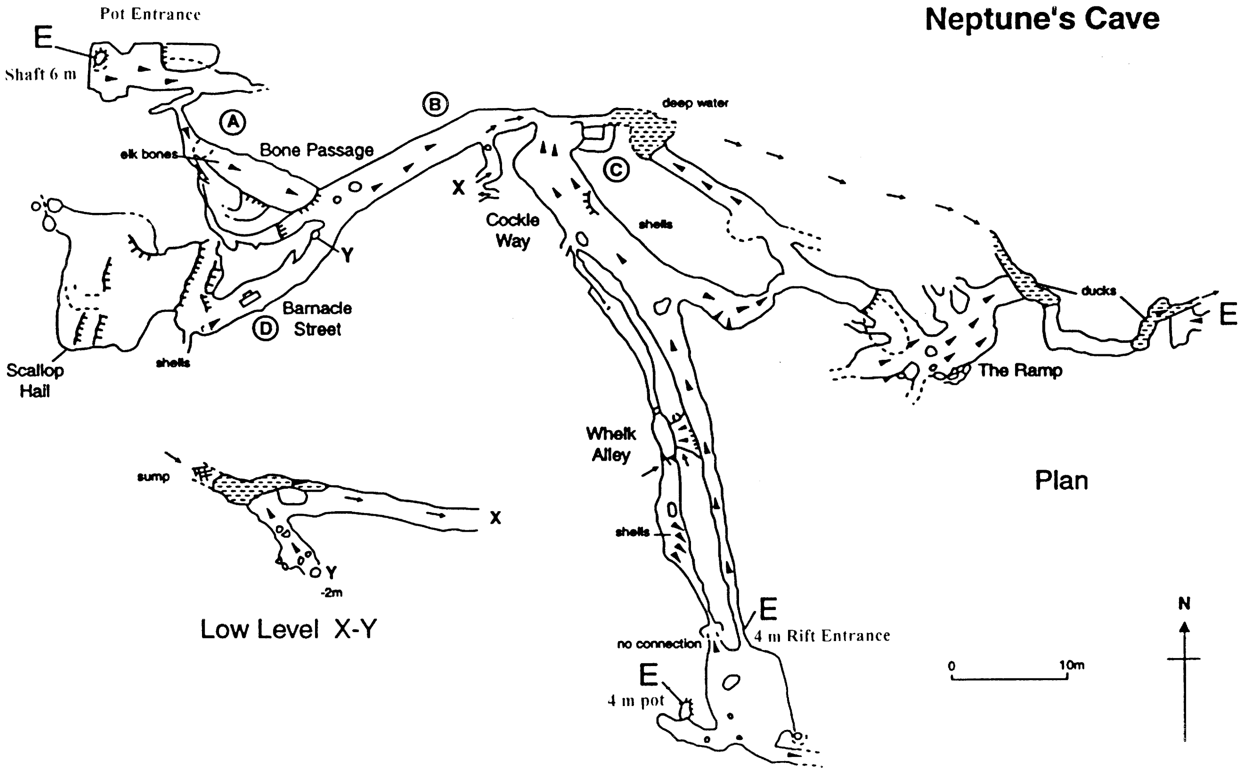

Fig. 2. Plan of Neptune's Cave, Svartdal, Brønnøy, Norway, showing the various entrances (E) and the four collection sites A, B, C and D. After Newton (1999).

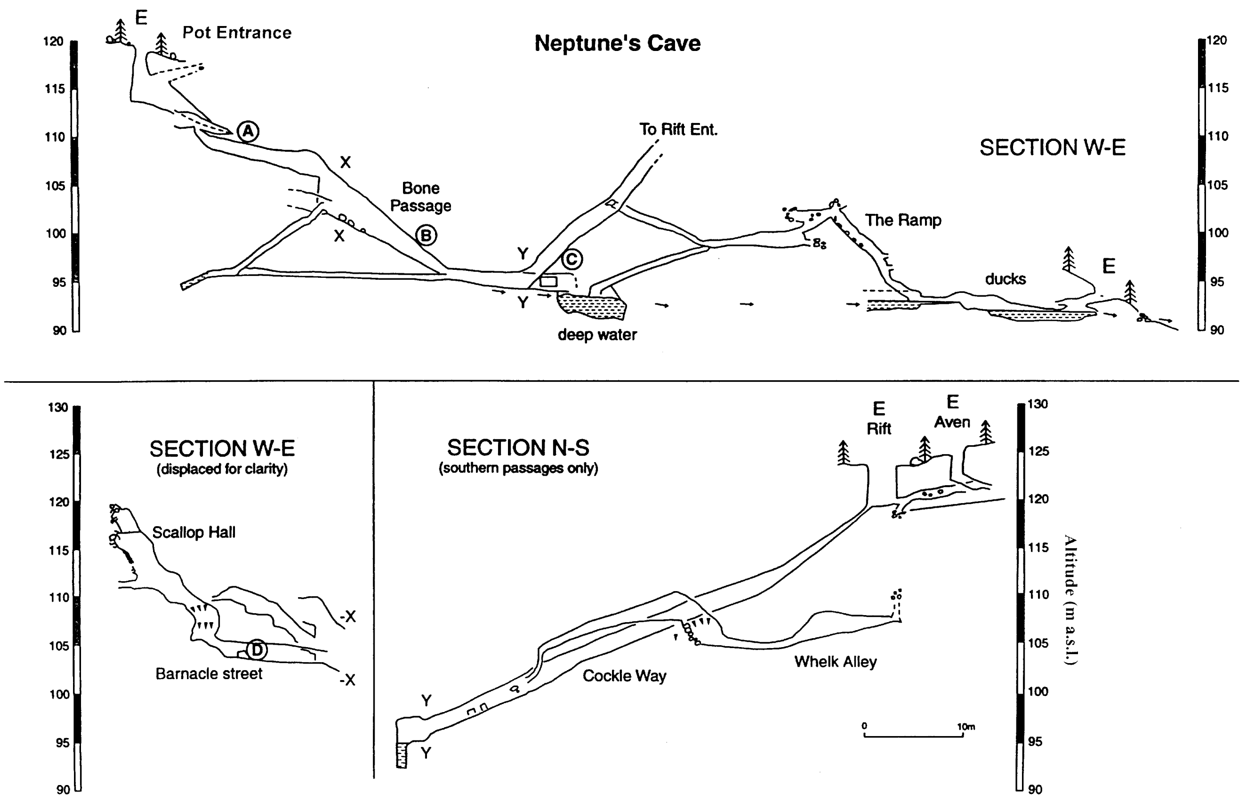

Fig. 3. Neptune's Cave W–E and N–S sections showing the altitudes of the entrances and of the collection sites A, B, C and D. After Newton (1999).

Table 1. Selected karst caves and deposits in the Velfjord area.

No.	Karst cave	UTM coord. (WGS 84)	Highest part (m a.s.l.)	Lowest part (m a.s.l.)	YD uplift (m)	Deposits	References
1	Svartdalgrotta	UN 8208 4465	180	127	145	No marine deposits, but an active cave	Newton (1999)
2	Neptune's Cave	UN 8248 4455	126	93	145	5 deposit types (see text)	Newton (1998, 1999)
3	Barnacle Cave	UN 8253 4430	142	140	146	Uncollected and unidentified barnacles	Newton (1998, 1999)
4	Draugenshullet	UN 8278 4420	137	124	147	Uncollected and unidentified barnacles	Newton (1998, 1999)
5	Aunhattenhule 1	UN 9457 4950	111	105	158	No marine deposits reported	Hoel (1906), St.Pierre & St.Pierre (1980)
6	Aunhattenhule 2 (shells found 'on and in the wall' at the cave mouth)	UN 9459 4951	121	116	158	*Saxicava pholadis* (L.): many. *Balanus creratus* [*sic*: probably *cretanus*] (Brug., Darw.): one example. *Pomatoceros tricuspis* (Ph.): many.	Hoel (1906), St.Pierre & St.Pierre (1980)
7	Aunhattenhule 3 (in bored holes in walls and roof at the entrance)	UN 9459 4947	139	132	158	*Saxicava pholadis* (L.): many. *Pomatoceros tricuspis* (Ph.): fragment	Hoel (1906), St.Pierre & St.Pierre (1980)
8	Naustvik holes	UN 850 559	24	24	140	*Saxicava*	Hoel (1906), St.Pierre & St.Pierre (1980)
9	Hegga Quarry Cave (visited in 1983 but now quarried away)	UN 866 576	*c.* 22?	*c.* 20	141	1 m by 3 m 'blanket' of fish bones, 1 cm thick, where a shoal of fish had been washed in	S.-E. Lauritzen, pers. comm. (1998), Olsen *et al.* 2001: p. 39).
10	Football Pitch Cave D	UN 7121 6386	27	25	117	Bored holes	St.Pierre & St.Pierre (1980)

geologists. Grønlie (1975: p. 472) mentioned shells in raised beaches in Vefsn and Grane kommunes that are *c.* 30 km east of Velfjord. Large non-carbonate coastal caves (11–16) occur at elevated situations near Brønnøysund (e.g. Sjöberg 1988), without published records of marine sediments. Faulkner (2005) concluded that the phreatic passages in Neptune's Cave were formed by dissolution in fast-flowing glacial meltwater along subglacial waterways during a phase of Weichselian deglaciation prior to deposition of its various organic materials.

Collection sites and deposits in Neptune's Cave

Five types of fossil were collected from Neptune's Cave: mammal bones, marine molluscs, barnacles, foraminifera and pollen. Figures 2 and 3 show the four collection sites (A, B, C and D). Shell collecting was not exhaustive.

Site A (altitude 109 m a.s.l.)

Site A is in the descending 1 m by 1.5 m Bone Passage, *c.* 4 m from the small entry tube. A thin undisturbed layer of organic unconsolidated gravelly clay lies on the floor. It contains uncollected shell fragments at the top of a sediment sequence that leads intermittently to Site B. Four large animal bones (B1–B4) were collected from a small triangular bedrock shelf on the south wall of the passage, just above the level of the highest clay deposit (Fig. 4A).

Site B (altitude range 99–100 m a.s.l.)

Lower down Bone Passage, here enlarged to 2 by 3 m, Site B is on the floor that slopes at *c.* 30°. Large marine shells lay at this site, in a 20 cm thick chaotic matrix of unconsolidated shelly gravelly mid-brown clays and clayey sands that lacks stratigraphy and contains stalagmitic fragments and scattered angular rocks up to 20 cm in size (Fig. 4B). A few marine molluscs were collected from the surface at Site B in 1997. Many more shells and fragments of various sizes were collected into sample boxes S1 and S2 in 1998 from an area $<1\,m^2$, mainly from the surface of the matrix, but also from depths up to 15 cm. A 1 kg bulk sediment sample SC1 was also obtained.

Site C (altitude 99 m a.s.l.)

Site C is on the east side of Cockle Way (*c.* 5×2 m), *c.* 7 m from the junction with Bone Passage, at a sloping bank of 0.5 m of homogeneous black soft silt kept moist by a trickle of water. Many small shells (S3) were collected from the surface of this silt and from a small gully at its western edge, where shells had been deposited by the trickling water. Indeterminate unattached barnacle

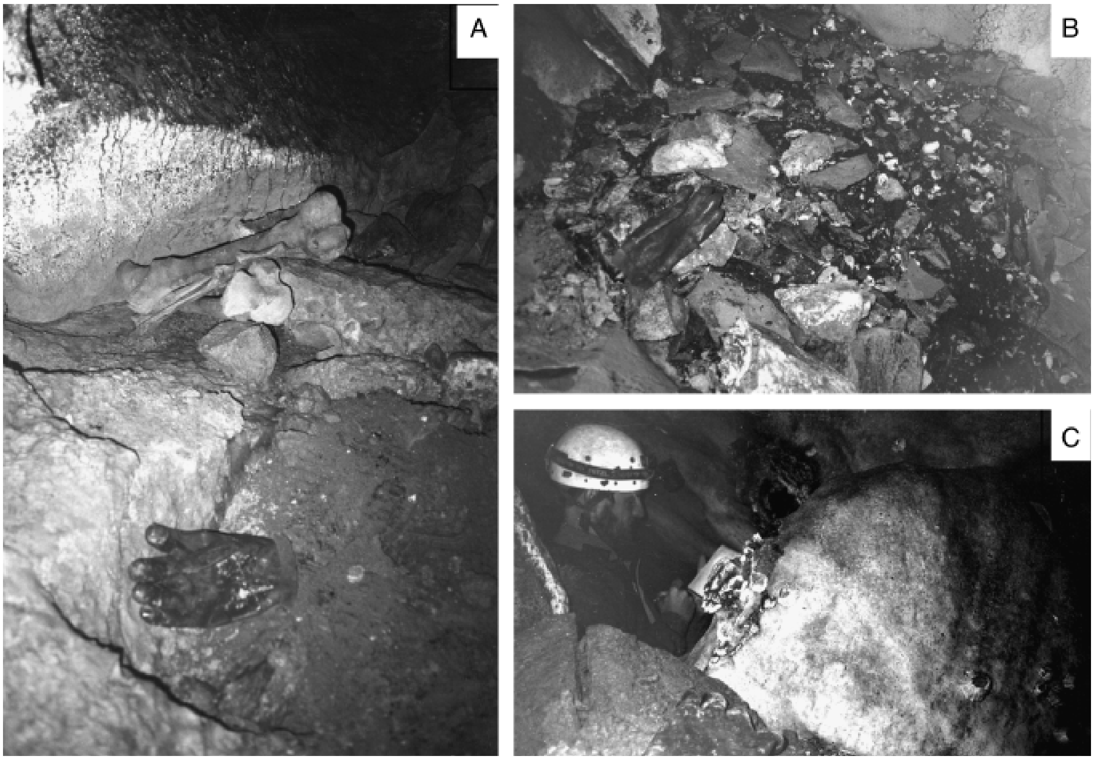

Fig. 4. Neptune's Cave collection sites. Photos by T.L.F. A = Site A. The four elk bones *in situ* on a triangular shelf above a floor of organic unconsolidated gravelly clay. Glove for scale. B = Site B. Marine shells interspersed with clastic sediments. Glove for scale. C = Site D. Attached barnacles. Cave surveyor for scale.

fragments were also observed. Being below the levels of the other barnacle sites, these fragments could have been washed there, probably from the Rift Entrance.

Small stalactites, straws and curtains occur in the roof of the passage at Site C that are $\leq$20 cm long and of presumed Holocene age. A loose stalagmitic cap recovered from the base of the slope below Site C in 1997 measured *c*. 20 cm in diameter and had a thickness of *c*. 1 cm. U-series dating was attempted at its base and at its top by Professor Stein-Erik Lauritzen at the University of Bergen, but heavy contamination with thorium makes the derived Holocene ages meaningless.

Site D (altitude range c. 103–104 m a.s.l.)

Two shells were collected at Site D, in Barnacle Street (2.5 by 1.5 m), one being clean; scrapings were later taken from the other (S4). Sparsely scattered barnacles (S5) were attached to the passage roof and walls above floor level and to the sides and top of a 1 m high fallen limestone block (Fig. 4C).

Methods

The altitudes for the Neptune's Cave entrances were determined using an altimeter standardized twice at the surface of Ursvatn (48 m a.s.l.) on 22 July 1997. Linear interpolations were made for the change in barometric pressure over time. This method usually gives repeatable results within $\pm$2 m. The cave itself was surveyed with tape, compass and clinometer on 23 July 1997 (Newton 1999), from which Figs 2 and 3 have been derived. They have internal altitude errors of perhaps $\pm$2 m.

Animal bones B1–B4 were collected by T.L.F. on 10 July 1998 and wrapped and stored dry prior to identification. Individual marine shells and barnacles collected in 1997 and 1998 were later scraped clear of excess sand and sediment, washed and cleaned by brushing in deionized water, and then identified. The scrapings and washings were individually stored in labelled bottles prior to examination for pollen, spores and foraminifera by C.O.H. in 1999, while both authors were based at the University of Huddersfield, UK. Sediment sample SC1 was collected into a plastic box and kept refrigerated prior to dating. Pollen and spores were extracted from sediment samples and from scrapings and washings from macrofossils by boiling the material for 10 min in 5% KOH solution, then sieving on nominal 7 μm nylon mesh to remove fines. Sand and silt were removed by 'swirling' on a clock glass. The concentrate was stained with fuchsin and mounted in glycerin gel. All palynomorphs were examined under $\times$400 and $\times$1000 magnification and counted.

Barnacles, molluscs, bone and organic sediment material were radiocarbon-dated at Beta Analytic, Miami, USA in 2000–2001. In all cases, pretreated samples provided sufficient carbon for accurate measurements, and analyses went normally. The measured or estimated $^{13}C/^{12}C$ and $^{18}O/^{16}O$ ratios were calculated relative to the Pee Dee Belemnite (PDB) international standard. Radiocarbon ages calculated from the ^{14}C content measured in a scintillation counter were normalized to $-25‰$ $\delta^{13}C$ for isotopic fractionation from the measured $^{13}C/^{12}C$ ratios to achieve the Conventional Radiocarbon Age (using Beta Analytic terminology).

Deposit identifications

Animal bones

B1–B4 were identified in 1999 by Andrew Currant at the Natural History Museum, London as left femur, right ulna, left tibia (50 cm long), right radius (conjoins with the right ulna), all being attributable to elk, *Alces alces* (Linnaeus 1758), which was an early colonizer after the disappearance of local ice. They could plausibly belong to one single adult, possibly female, individual. The bones showed no signs of impact, gnawing or human activity, suggesting that the animal died close to its retrieved location in the cave, probably after falling through thawing snow to the base of the Pot Entrance shaft, where bacterial action decomposed it to a clean skeleton within a few years. Surface pitting could have arisen from corrosion by salt spray carried 2 km east by wind from Ursfjord.

Marine molluscs

The molluscs collected at each site were identified in 1999 by Nora McMillan, while at the Department of Zoology, Liverpool Museum, UK, as presented in Table 2 and as considered further in Table 3. The names used are those of Smith & Heppell (1991). Almost all the material was of single valves of lamellibranchs. All species still occur in modern seas off Norway (Høisæter 1986; Seaward 1990), and commonly live to depths of several tens of metres (Van de Plassche 1986). The variety and worn nature of the shells indicate that they did not live in the cave, but formed a strandline deposit, later washed into the cave. Each individual specimen might therefore have experienced two stages of post-mortem transportation: firstly from its *in situ* position to a strandline above the cave, and secondly to its location within the cave.

Barnacles

The barnacles from Site D were extremely fragile, and most broke when prized away with a knife. Their diameters were typically 35 mm, with interiors filled with sand. No juvenile specimens were observed. One intact specimen was collected, together with *c.* 15 fragments (S5). A few weathered barnacles also remain attached to the walls at the foot of the Rift Entrance, at an altitude of 120 m a.s.l. The barnacles were all identified by Nora McMillan (Table 2) as *Balanus balanus* (L.). A sample of fine silty material washed off barnacles was submitted to Dr. Alan Bowden at Liverpool Museum on 3 February 1999. He reported: 'The sample only contained a few shell fragments, silica and flakes of mica. One beetle wingcase noted. No foraminifera nor ostracods'.

Foraminifera

Scrapings from the shells S1 and S2 revealed one badly corroded foraminifer, probably *Hyalina balthica*.

Pollen

Scrapings and washings from shell samples S1–S5 and scrapings from a fine brown deposit on all bone surfaces B1–B4 contained pollen. The results of their palynological analysis are given in Table 4. The assemblages were all extremely small and very poorly preserved, and in many ways are very similar. They are therefore discussed together. Material was 'thin' and commonly torn and crumpled. Samples were heavily dominated by Pteropsida (monolete, psilate fern spores) and *Lycopodium* spp., generally *Lycopodium* aff. *clavatum*. Some *Dryopteris*-type fern spores were present and it is probable that many of the Pteropsida were, in fact, degraded internal bodies of *Dryopteris*-type spores. Also present were small numbers of *Pinus*, *Picea*, *Betula*, *Alnus*, Coryloid (*Corylus* or *Myrica*), Rosaceae, Poaceae, *Botrychium* and *Sphagnum*. Amoeboid cysts were present in two samples.

These assemblages show a consistent taphonomic bias: it is instantly apparent that no environment on earth is characterized by assemblages of this type. Recently deposited cave sediments are commonly full of Pteropsida spores, because ferns are typical of the cave-mouth flora. Ancient cave sediments also tend to contain rather high numbers of other taxa known for their resistance to corrosion (e.g. Bramwell *et al.* 1984; Gale & Hunt 1985). In the same way, at Neptune's Cave, taxa such as *Pinus*, *Picea*, *Botrychium*, *Lycopodium*, *Hupzeria*, Pteropsida and *Sphagnum* are all likely to be extremely corrosion resistant (cf. Havinga 1984). Outside caves, assemblages full of corrosion-resistant palynomorphs are common in subsoils (Keatinge 1983; Dimbleby 1985; Hunt & Coles 1988) and in fluvial sediments (Hunt 1994).

It is hypothesized, therefore, that the pollen entered the cave as a component of eroded soil profiles, some time significantly later than the original deposition, and after considerable weathering. Some deductions can be made concerning the origin of the palynomorphs.

Table 2. Identification of the molluscan shells and cirripedes from Neptune's Cave by Nora McMillan.

Cave site	Box	Year collected	Identification	Size (mm)	Comments
B		1997	*Chlamys islandica* (Gmelin)	115×110	Single scallop, quite exceptional in size
B		1997	*Mya truncata* (L.)		One valve plus broken small valve
B		1997	*Tridonta elliptica* (Brown)		Single valve [formerly *Astarte elliptica*]
B	S1	1998	*Modiolus modiolus* (L.)		Two hinge fragments and two other fragments
B	S1	1998	*Chlamys islandica* (Gmelin)	78	One imperfect valve
B	S1	1998	*Tridonta elliptica* (Brown)		Valves abundant. By far the most numerous species present
B	S1	1998	*Mya truncata* (L.)	50×*c*. 65	A large thick valve. Several smaller valves
B	S1	1998	*Hiatella arctica* (L.)	48 and 46	Two large valves
B	S2	1998	*Modiolus modiolus* (L.)		A hinge fragment. Some scraps of nacre present are referable to this species
B	S2	1998	*Chlamys islandica* (Gmelin)		Two good-sized fragments, one very thin
B	S2	1998	*Tridonta elliptica* (Brown)		Valves abundant, all much worn
B	S2	1998	*Macoma calcarea* (Gmelin)	25×34	Single valve
B	S2	1998	*Mya truncata* (L.)		Two valves, one right and one left, plus a few fragments
B	S2	1998	*Hiatella arctica* (L.)	50 long	A valve, with another slightly smaller and a few fragments
B	S2	1998			A single gastropod fragment, probably a bucinid
C	S3	1998	*Modiolus modiolus* (L.)	80×45	A large valve, another valve (with calcrete encrustations all round the margin) and two other fragments
C	S3	1998	*Chlamys islandica* (Gmelin)	70×65	Single valve
C	S3	1998	*Tridonta elliptica* (Brown)		Valves abundant
C	S3	1998	*Tridonta montagui* (Dillwyn)		Three valves
C	S3	1998	*Mya truncata* (L.)	40×50	Two valves which appear to be a pair though not in apposition when found. Also a young valve
C	S3	1998			Barnacle fragments *indet*.
D	S4	1998	*Modiolus modiolus* (L.)	108×50	Single isolated elongate valve that was clean *in situ*
D	S4	1998	*Mya truncata* (L.)	30×45	Single valve
D	S5	1998	*Balanus balanus* (L.) [*porcatus* da Costa]		Crustacea: Cirripedia (barnacles). One intact specimen, with *c*. 15 fragments

Grassy environments are suggested by *Botrychium* and Poaceae. The Lycopods, *Sphagnum* and the testate amoeba suggest areas of bog. *Pinus*, *Picea*, *Alnus* and *Betula* probably indicate Holocene woodland.

Age of deposits from Neptune's Cave

Prior to the last deglaciation, Neptune's Cave had been covered by ice with a thickness that probably varied from >2000 m at the Last Glacial Maximum to >100 m in the YD. It is extremely unlikely that internal deposits from Weichselian, or earlier, interstadials could have survived in the cave because such deposits would have been flushed out of the cave during its inundation as each of the large ice sheets melted. Any injection of glacier ice, or freezing of internal water, is also likely to have damaged and loosened cave deposits prior to flushing out. Thus, the unconsolidated deposits in Neptune's Cave can be expected to date from the late YD or from the Holocene. The complete absence of *Portlandia arctica* and perhaps *Astarte borealis* that are specific to high-arctic or YD waters supports an early Holocene environment for the marine molluscs, whereas the absence of the common mussel *Mytilus edulis* agrees with an environment before the start of the Preboreal and Boreal warm periods (Bondevik *et al.* 1999, 2001).

The barnacles (S5) contained good biological structure, and being calcitic make especially good material for radiocarbon dating (Pirazzoli *et al.* 1985). Scanning electron microscopy revealed that most of the mollusc sample, S1+S2, was composed of fine-grained, secondary, shell. The replacement fabric was finely crystalline, with some dissolution evident near the edges, and with a remnant of the original shell structure in one small area. It is assumed that the source of the recrystallized material was from the shells themselves, being part of the slow natural process of recrystallization from aragonite to calcite that occurs in slightly damp environments. The only mollusc species from Neptune's Cave that Mangerud *et al.* (2006) advised should be avoided for dating is *Macoma calcarea*, and this was not included in the dated sample. Because the dates obtained are within the expected timescale, contamination by carbon exchange with 'old' limestone or later CO_2 is not suspected for either sample type. Additionally, Faulkner (2005) deduced that local cave passages did not continue to enlarge by dissolution when submerged by the sea, so that the barnacles are unlikely to have ingested any Palaeozoic carbonate despite being attached to it. Table 5 gives the Conventional Radiocarbon Ages for the barnacles and molluscs to be 10 280±90 and 10 010±80, respectively, where this is the ^{14}C age BP before correction for the local marine reservoir age.

Table 3. Mollusca species, their location in Neptune's Cave and their present ranges of occurrence.

Species	Cave sites	Occurrence	Modern depth range (m)	Salinity range ‰ – ‰	Comments
Modiolus modiolus (L.)	B,C,D	A common northern species ranging from Iceland south to the Bay of Biscay, but not in high-Arctic seas.	5–150	35–20	Horse mussel. Salinity range from Brattegard (1966)
Clamys islandica (Gmelin)	B,C	Arctic and discontinuously circumpolar. In Norwegian waters it extends as far south as Stavanger (Ockelmann 1958: p. 65).	20–320		Two imperfect specimens from Site B are of very thin texture. Macginitie (1959: p. 155) described the variation in sculpture and thickness of the valves of Recent specimens
Tridonta elliptica (Brown) [formerly *Astarte elliptica*]	B,C	Panarctic and boreal, extending south only to the northern part of Britain.	14–160		These have necessarily been identified on conchological grounds only; for satisfactory determinations, microscopic examination of the periostracum is needed (Ockelmann 1958). These water-worn shells lack all periostracum.
Tridonta montagui (Dillwyn)	C	Also panarctic-boreal, but extending south to the Bay of Biscay	10–270		Both these species of Tridonta live offshore in sandy mud and gravel
Macoma calcarea (Gmelin)	B	Another panarctic and circumpolar species, ranging south to the Faroes and the Kattegat	10–70	Full to brackish near ice fronts	Andersen *et al*. (1981)
Mya truncata (L.)	B,C,D	Panarctic and circumpolar; widely distributed in the Arctic and as far south as La Rochelle, France	Tidal–73	As above	This species likes to burrow into mud, indicating that the local coastline was not cliff-bound
Hiatella arctica (L.)	B	Panarctic-boreal and common from the Arctic to the Mediterranean	0–1400	35–20	Primarily a shallow-water species. Brattegard (1966)

The value of the local marine reservoir age, its variation along the Norwegian coastline and its change over time are the subjects of continuing debate (Mangerud & Gulliksen 1975; Bondevik *et al*. 1999, 2006; Mangerud *et al*. 2006). It might also be reduced in the vicinity of Neptune's Cave by dilution by fresh water if in 'head of fjord' conditions. The extent of seawater dilution and shell growth temperature can commonly be deduced from the linear relationships between salinity, temperature and the carbon and oxygen stable isotope compositions of *in situ* marine shells (Mook 1971; Eisma *et al*. 1976; Van de Plassche 1986: p. 540). Because the values of δ^{13}C for the barnacles and molluscs of +1.0 and +1.5‰ lie within the range 0–2‰, these specimens lived in undiluted seawater and were not subjected later to a large degree of recrystallization in a freshwater environment. Plotting the measured values of δ^{18}O of +2.4 and +2.5‰ (Table 5) on to the graph of Eisma *et al*. (1976: fig. 2) suggests that the calcification of both shell types occurred at a temperature of *c*. 7.5 °C (not shown). This is within the present sub-halocline/thermocline temperature range of 6–9 °C for Norwegian fjords in summer, when shell growth is concentrated (A. J. Southward, pers. comm. 2001). Hence, both the barnacles and molluscs experienced environmental conditions similar to present and, as also deduced by Bondevik *et al*. (1999) for shells in southern Norway, the local present coastal reservoir age should apply.

Taking the early Holocene reservoir age in southern Norway as 360±20 yr from Bondevik *et al*. (2006) and using the 40 yr increase northward reported by Mangerud & Gulliksen (1975), while recognizing that the salinity of Norwegian Coastal Water varies south to north from below 33‰ towards 35‰, it appears that a reservoir age of *c*. 400 yr and a salinity of *c*. 34‰ are the correct values to use for Velfjord at present and in previous interstadials. However, all other locally reported radiocarbon dates discussed herein are based on a reservoir age of 440 yr and this age will be used in further discussion to maintain consistency. Such dates have yet to be calibrated to calendar years, and therefore calibration of the marine shell ages is not attempted here. A 440 yr reservoir age yields atmospheric mean ^{14}C ages of 9840±90 and 9570±80 yr BP for the demise of the barnacles and molluscs. The age of bone B4 is 5100±70 yr BP. The date for the sample of organic sediment SC1 of 1780±70 yr BP represents a weighted average of all the organic carbon components, less rootlets, fulvic acid and carbonates removed in the pretreatment.

Table 4. The distribution of pollen species in the samples from Neptune's Cave.

Sample Host material Cave site	S1 nos. Shell B	S1 % Shell B	S2 nos. Shell B	S2 % Shell B	S3 nos. Shell C	S3 % Shell C	S4 nos. Shell D	S4 % Shell D	S5 nos. Barnacle D	S5 % Barnacle D	B1–B4 nos. Bone A	B1–B4 % Bone A
Pinus	1	0.85	1	0.72	7	11.29					1	3.85
Picea			2	1.44								
Betula									1	7.69		
Alnus									3	23.08		
Coryloid	1	0.85										
Rosaceae									1	7.69		
Poaceae	1	0.85							1	7.69		
Dryopteris type	10	8.55	12	4.32								
Botrychium					2	3.23						
Lycopodium aff. *clavatum*	32	27.35	41	29.50	1	1.61					3	11.54
Hupzeria selago							3	100				
Pteropsida	70	59.83	83	59.71	50	80.65			7	53.85	22	84.62
Sphagnum	2	1.71			2	3.23						
Total pollen and spores	117		139		62		3		13		26	
Testate amoeba									2		3	

Table 5. Radiocarbon ages of four types of deposits from Neptune's Cave. Asterisk denotes *Hiatella arctica* fragment.

Sample type	Barnacles	Molluscs	Bone	Organic sediment
Laboratory no.	Beta-148614	Beta-140995	Beta-146854	Beta-142744
Cave site	D	B	A	B
Sample identification	S5	S1+S2	B4	SC1
Sample detail	20 g fragments of *Balanus balanus*. Good biological structure	55 g fragments of most of the identified species, excluding *Macoma* (Table 2).	*Alces alces* (L.): right radius. 630 g, no fungal contamination	1 kg. No indication of mould
Pretreatment	Acid etch	Acid etch	Bone collagen extracted with alkali	Acid wash. Bulk low carbon analysis
SEM result	Not required	Replacement fabric	Not applicable	Not applicable
Measured radiocarbon age (yr BP)	9850±90	9580±80	5040±70	1780±70
$^{13}C/^{12}C$ ratio (‰)	+1.0	+1.5	−21.0	−25.0 (estimated)
$^{18}O/^{16}O$ ratio (‰)	+2.4	+2.5*		
Conventional radiocarbon age (^{14}C yr BP)	10 280±90	10 010±80	5100±70	1780±70
Assumed local reservoir age (^{14}C yr).	400	400	Not applicable	Not applicable
Deduced atmospheric radiocarbon age (^{14}C yr BP)	9880±90	9610±80	Not applicable	Not applicable
Atmospheric ^{14}C age (yr BP), based on 440 yr reservoir age	9840±90	9570±80	Not applicable	Not applicable

Uplift and deglaciation

Following Weichselian glacio-isostatic depression, Fennoscandia started to rebound very quickly with the removal of the ice burden in the rapidly warming Holocene (e.g. Mörner 2003). The dashed YD isobase lines on Fig. 1 are extrapolations and interpolations from the YD isobases mapped by Sørensen *et al.* (1987). These isobases are also in general agreement, by extrapolation, with altitude/age information provided by Grønlie (1975). Although sea-level curves have yet to be published for the Velfjord–Tosenfjord area, they are available for other parts of the Norwegian coastline (Ramfjord 1982; Svendsen & Mangerud 1987; Møller 1989; Bergstrøm 1992, 1995). These curves show that *c.* 50% of the Holocene uplift occurred within the first 1000 years and they all have 'elbows' at *c.* 8500, when the last ice melted. Svendsen & Mangerud (1987) drew

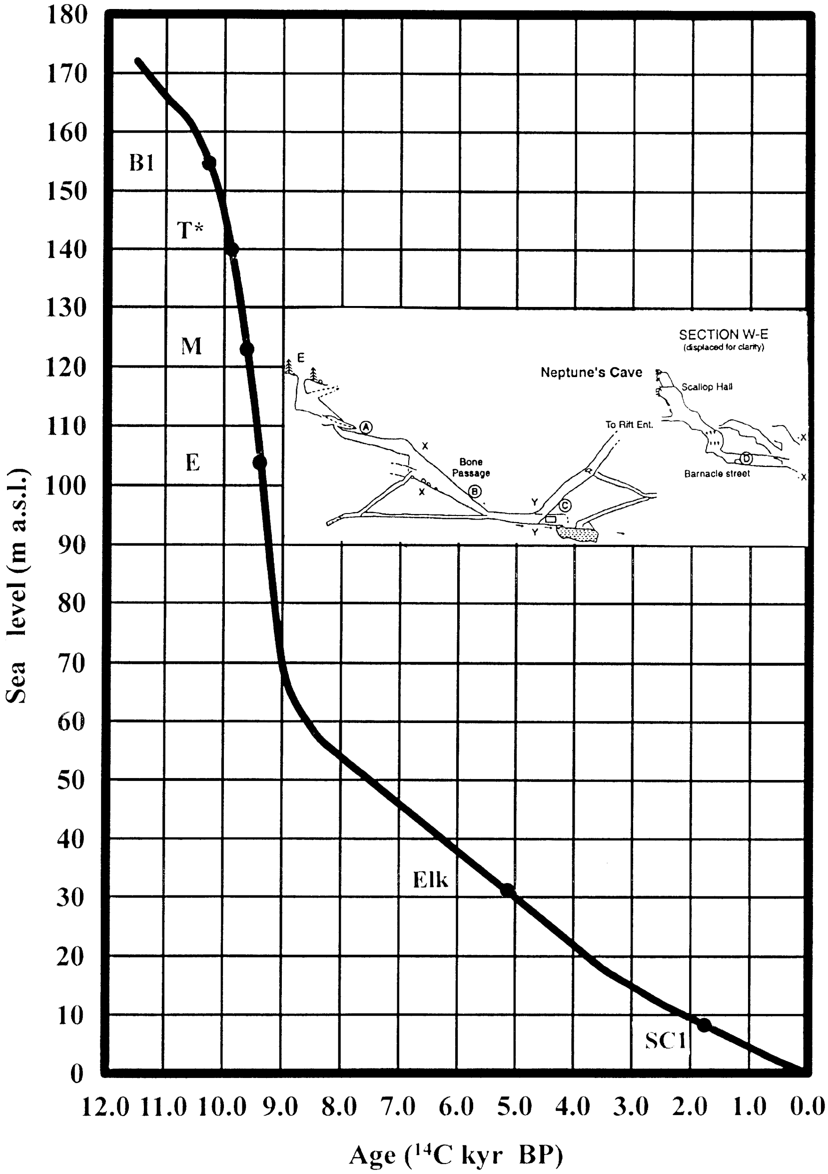

Fig. 5. Holocene sea-level curve for Neptune's Cave constructed for a 146 m YD isobase from the composite 150 m isobase sea-level curve given by Svendsen & Mangerud (1987: fig. 12). Events shown: B1 = Neptune's Cave became ice-free; T* = Age of the Terråk moraine and of the demise of the barnacles; M = Demise of the molluscs; E = Emergence of the barnacles a.s.l.; Elk Demise of the elk; SC1 = Age of the organic sediment. Sections of Bone Passage and Barnacle Street are inserted at correct altitudes.

isobases and a composite shoreline diagram that they considered valid from western Norway to just north of Trondheim (although perhaps not further north: p. 128). Their fig. 12 shows a corresponding suite of sea-level curves for YD isobases in the range 110–160 m, i.e. equivalent to those going inland at Velfjord. It is assumed herein that for each applicable YD isobase the sea-level curve at Velfjord does have a similar shape, despite the reservation. Figure 5 is an assumed Holocene sea-level curve for Neptune's Cave at a 146 m YD isobase, constructed by under-following the curve given by Svendsen & Mangerud (1987: fig. 12) for the point 130 km southeast from the hinge line along their projection, which is at the 150 m YD isobase.

The deglacial eastward retreat of the ice margin across Norway was mapped by Andersen & Karlsen (1986) and subsequently refined by Olsen (1997). Andersen *et al.* (1981, 1982) used marine shells from the Nordland coast to date marginal moraines that represent four glacial events (Fig. 1): A (12 300±200), B (Tjøtta: 11 000–10 300), C (Nordli: 10 100±200) and D (9550±200 yr). The Tjøtta event suggests a cooling incursion of arctic water with the YD glacial advance at 11 000 yr BP. The glaciers retreated again after 10 500 yr BP, but re-advanced slightly at 10 100 yr BP. Three ages were obtained for the Velfjord area: S* (Steindal: 10 300±250), B* (Bogen: 10 330±250) and T* (Terråk: 9890±230 yr). S* and B* were correlated with the Tjøtta event. The roughly parallel nature of the moraines indicates the southeastwards retreat of the local ice margin, when much of the local area was still below sea level. A marine environment followed a calving tidewater glacier as it retreated through a valley system indicated by the line XY, towards the ice-filled Tosenfjord. B_1 and B_2 represent the times that the ice margin passed Neptune's Cave and a narrow col Y at 95 m a.s.l. Taking the age of the Velfjord B moraine as 10 330±250 yr, then the ice margin travelled a distance of *c.* 29 km via Ursvatn to the moraine east of Tosenfjord by 9890±230, giving a rate of *c.* 66 m $^{14}C\ yr^{-1}$, so that B_1 and B_2 occurred at 10 240±250 and 10 060±250 yr BP. Hence, neither the barnacles nor the molluscs lived in seawater that was under a permanent cover of ice, as agreed by their common calcification temperature of *c.* 7.5 °C.

The interpolated shapes of the moraines that curve eastwards beyond the 415 m deep Tosenfjord suggest that 'sideways' melting by the sea occurred via the three valleys east of the submerged col at Y, initially creating three saline embayments in the side of the fjord glacier. There was probably a later jökulhlaup or 'superflood' (Fisher *et al.* 2002; Rudoy 2002), when the sea breached the ice barrier between it and a dead-ice lake at the head of the fjord. The surface of such a lake would be near the level of the continuing ice sheet at *c.* 400 m a.s.l. (Faulkner 2005), i.e. *c.* 235 m above the surface of the sea, which was then 165 m a.s.l. (Fig. 5, with 25 m added for the higher isobase). From the topography of Tosenfjord, ~7 km^3 of glacial meltwater may have surged seaward, an enormous flood that would take many hours to subside.

Life and death of the barnacles

When Neptune's Cave became ice-free at B_1 = 10 240±250 yr BP, the sea surface was then *c.* 154 m a.s.l. (Fig. 5), giving a depth to the roof of Barnacle Street of *c.* 50 m. However, the glacial meltwater that immediately flowed through the valley at Ursvatn probably inundated the cave, making it unable to support marine life for some time. *Balanus balanus* is a North Atlantic cold-water species that lives below the low-water mark of equinoctial spring tides and below 10 m depth in the open sea. They are euryhaline, can resist freshwater for short periods and can acclimatize to seawater diluted to a salinity of 17‰ (Foster 1970). With increasing salinity, the small barnacle colony became established in Neptune's Cave, but died at 9840±90 yr BP, when the sea was at *c.* 140 m a.s.l. (Fig. 5), giving a water depth that was as still as great as *c.* 36 m. So, why did the barnacles die?

Assuming that the colony did not simply die of old age, their demise was likely caused by an environmental change. The barnacles might have lived below the halocline (commonly above 50 m in Norwegian fjords in summer) that separates upper, warmer, low salinity, estuarine, water from a well-ventilated, intermediate, layer of mixed estuarine water and water from the continental shelf (Sejrup *et al.* 2001). Although it is possible that the barnacles died by emerging above the halocline, isostatic elevation is relatively slow and there is no evidence that the barnacles migrated to the lowest levels to maintain a saline environment, suggesting instead that the salinity changed rapidly.

The death of the barnacles at 9840±90 cannot be distinguished from the age of the Terråk T* moraine at 9890±230 yr BP, strongly suggesting that the two events are related and that a jökulhlaup that swept along line YX rapidly lowered salinity and killed the barnacles. The coincidence of the two dates also hints that Tosenfjord was deglaciated in one single dramatic event. Because a proportion of the icemelt from many valleys draining to the fjord continued to flow to the sea via route YX, salinity may have remained too low for a new barnacle colony to be established in Neptune's Cave. The outside salinity had normalized before 9570±80 when the molluscs died, but by this time the sea surface was at *c.* 122 m a.s.l. (Fig. 5), giving a water depth of only *c.* 18 m that perhaps could not offer a refuge below a halocline. The attached barnacle shells at 104 m a.s.l. filled with sand and emerged from the sea at *c.* 9400 yr BP (Fig. 5), *c.* 440 ^{14}C yr after their demise. Their long preservation probably relied on an extremely well-protected position in still water, and by the complete absence of sunlight (Pirazzoli *et al.* 1985). *Balanus balanus* is also one of the most robust barnacle species, with a thick shell and good non-porose basis (A. J. Southward, pers. comm. 2001).

Life and death of the molluscs

The S1+S2 mix of various mollusc shells within the dated organic sediment SC1 (probably redeposited soil) at Site B and the nature of their damage suggest that they originally formed part of a strandline that was washed in via the Pot Entrance by a terrestrial, meteoric, event at 1780±70 yr BP. The molluscs probably lived in the vicinity of the still-submerged Neptune's Cave, whose Pot Entrance at 119 m a.s.l. emerged above the sea at *c.* 9520 yr BP (Fig. 5). The collected molluscs could therefore have died over a maximum time range from 9840±90 (the deduced melting of Tosenfjord) to 9520 yr BP, a time range that nicely includes their measured age of 9570±80 yr BP. They were likely deposited by high tides and/or storms in strandlines slightly higher than a maximum range of 140–119 m a.s.l. However, the maximum age of the oldest molluscs would equal the time when salinity (perhaps below a halocline still diluted by strong outflows from the melting ice sheet east of Tosenfjord) increased to a tolerable level, giving a narrower time range. Hence, all the mollusc shells at Site B might have similar ages around 9570±80 yr. Indeed, such a concentrating process may explain their density. The many unidentified and undated shells in Whelk Alley, which presumably entered via the Rift Entrance at 124 m a.s.l., indicate a deposit that is slightly older than 9570±80 yr. Nevertheless, both sets of shells may originate from the same strandline washed to an altitude above 119–124 m a.s.l. at about 9570±80 yr BP. Presumably, any older molluscs that lived in the vicinity at the same time as the barnacles were swept further out to sea by the Tosenfjord jökulhlaup, and not left as higher beach deposits waiting to be transported into the cave. The altitude of the Pot Entrance constrains isostatic elevation to be $\geq$119 m after 9570±80 yr BP for the 146 m YD isobase, only $\leq$3 m below the level indicated in Fig. 5.

It is postulated that the inwash event was initiated by a rare and extremely major flood, resulting from meltout and/or thunderstorm, which submerged the entire cave and caused water to flow from the Pot Entrance to Bone Passage via the small tube. As the flood developed, it mobilized unconsolidated beach deposits and soils, creating a 'bogburst', and redeposited them by mudflows into the cave. The absence of stratification in the Site B deposits and their survival rules out any similar later event. The different colour of the deposits at Site C implies that they arrived separately via the Rift Entrance. The absence of expected sand banks below the sandy barnacle shells suggests that they were washed away by the flood. There was clearly insufficient flow along Barnacle Street to sweep all the fragile barnacle shells off the walls, suggesting that any direct entrance had closed by that time.

The elk bones

The tube leading to Site A is too small to permit the passage of a complete elk carcass. It seems unlikely that either a partly decomposed mass of putrefying flesh and bones or a complete skeleton was carried there by a flood soon after the elk died at 5100±70 yr BP, because this would imply that floods of that magnitude occurred regularly, so that a later flood, and especially the one that occurred at 1780±70 yr BP, would have carried the bones away. It seems more likely that the bones were redeposited in the same event as the shells and organic sediment and that parts of the dismembered skeleton were carried only 16 m through the small tube at an early stage of that flood. Thus, the four undamaged bones were left on the small Site A ledge because the increased size of the passage reduced the water velocity, while the other remains were swept further down, and perhaps out of, the cave. A test showing that the elk bones only just sink in fresh water supports this concept. Because the pollen spectrum for their brown surface deposits is statistically indivisible from that of the pollen on the shells and barnacles (Table 4), it seems likely that all these pollen coatings were brought into the cave by the same flood. The submergence of the whole cave would also account for the heavy stalagmitic cap below Site C, which could have been brought from almost anywhere in the cave to that point, and for the rocks at Site B, which probably came from the base of the Pot Entrance. The absence of soil on the four elk bones suggests that their final deposition above floor level (Fig. 4A) preceded the actual mudflow, which was limited by the size of the linking tube, so that it only flowed along the floor of Bone Passage during a drier terminal phase of the bogburst.

Conclusions

Despite difficulties in using the dated molluscs and barnacles to determine palaeo sea levels, because they can live down to depths of 150 m, and despite the lack of stratigraphical context for all the deposits, they can be related to a plausible scenario for the deglaciation and emergence history of the Velfjord–Tosenfjord area. It is concluded that the *Balanus balanus* in Neptune's Cave lived for a relatively short period and died at 9840±90 yr BP, when a jökulhlaup collapsed a tidewater glacier in Tosenfjord and sent glacial meltwater through the cave. This date agrees with the previously published date for the Terråk moraine of 9890±230 yr BP, but with a reduced error margin. The death of the barnacles in normal seawater at *c*. 7.5 °C confirms that the ice margin had already passed overhead, providing a weak constraint on an event that was *c*. 400 ^{14}C yr earlier, according to interpolated local moraine dates. The individual molluscs that formed beach deposits above Neptune's Cave probably died relatively close together around 9570±80 yr BP, and no later than 9520±80 yr BP, so that they could be deposited above the Pot Entrance at 119 m a.s.l., which provides a minimum value for the subsequent local isostatic uplift. The next event of interest was the fall of an elk *Alces alces* into the same entrance shaft at 5100±70 yr BP. A major flood at *c*. 1780±70 yr BP probably filled the cave, bringing the four elk bones to their resting place, and leading to a bog-burst that transported soil and mollusc shells into the cave as a mudslide. Thereafter, the cave lay mostly undisturbed until its discovery in 1997.

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