Long-term changes in sediment type and cavernicolous bivalve assemblages in Daidokutsu submarine cave, Okinawa Islands: evidence from a new core extending over the past 7,000 years

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Abstract We analyzed sediments and cavernicolous bivalve assemblages within cored sediments recovered from the Daidokutsu submarine limestone cave, which occurs in Pleistocene limestone on the fore-reef slope of Ie Island, off Okinawa, Japan. We found sand-sized brown grains within sediments aged 7,000-6,000 cal BP, and identified ~~them~~ the grains as debris derived from a red soil layer developed in coastal zones around the Island. Temporal changes in the abundance of the debris suggest that water flow in the cave weakened at about 6,500 cal BP. Temporal changes in the cevernicolous bivalve assemblages indicate that the environmental conditions of the innermost cave area have gradually spread to the cave entrance over the past 5,000 years. These findings indicate that the filling of cavities within the reefal foundations of the cave has continued over time, resulting in a progressive decrease in the flux of water between the interior and exterior parts of the cave during at least the past 6,500 years. This indicates in turn a long-term decline in the functioning of the cryptic community within the reef as a source of the nutrients that support coral reef growth. Our findings regarding the distribution of debris from the red soil layer strongly support~~s~~ the occurrence of a mid-Holocene high-energy window, which represents a period of high wave energy prior to the formation of a reefal barrier.

Keywords　Coral reef・Submarine cave sediments・Cavernicolous bivalves・Soil・Environmental change

Introduction

Cavities in coral reefs are produced in a number of ways, including reef framework growth and the dissolution of limestone (Kobluk 1988). Such cavities constitute between 30 and 75% of the bulk volume of coral reefs (Garret et al. 1971; Ginsburg 1983) and between 60 and 75% of the total available reef surface (Jackson et al. 1971; Logan et al. 1984). The large area of reef made up of cavities is inhabited by sponges, bryozoans, brachiopods and other organismss. The biomass of the cryptic communities has the potential to extend beyond the reef surface (Hutchings 1974; Brock and Brock 1977; Meesters et al. 1991).

Previous studies have addressed the evolutionary significance of cryptic communities (Jackson et al. 1971; Jackson and Winston 1982; Gili et al. 1986; Harmelin 1997; Wörheide 1998; Kano and Kase 2000, 2008; Kano et al. 2002; Motchurova-Dekova et al. 2002; Ubukata et al. 2009) and the fluxes of various materials (e.g., dissolved oxygen, dissolved inorganic matter, dissolved organic matter, and bacterioplankton) in reef cavities (Fichez 1990a, 1990b, 1991; Richter et al. 2001; Scheffers et al. 2004; Van Duyl et al. 2006; De Goeij and Van Duyl 2007). However, we are unaware of any published studies that have searched for millennia-scale variations in the community of organisms in reef cavities, with the exception of Kitamura et al. (2007a).

Kitamura et al. (2007a) examined cavernicolous bivalve assemblages in surface and cored sediments within Daidokutsu submarine cave (29 m water depth) on the fore-reef slope of Ie Island (26º43'N, 127º50'E) (Fig. 1), Okinawa, Japan. The cave is developed in Pleistocene Ryukyu Limestone, having formed by the movement of underground water during periods of low sea level (Hayami and Kase 1993). The bivalve species

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living in the innermost area of the cave have become increasingly dominant over the past 5,000 years, while those living near the entrance of the cave have declined in abundance over this period (Kitamura et al. 2007a). This finding indicates that the environmental conditions of the innermost cave area have progressively extended to the entrance of the cave.

According to Kobluk (1988), most cavities in reefs are eventually filled with surface-derived sediments, cement, debris, and *in situ* skeletons of the cryptic community. On this basis, Kitamura et al. (2007a) concluded that the progressive infilling of cavities at Daidokutsu cave has resulted in a decrease in the flux of water between the interior and exterior parts of ~~Daidokutsu~~ the cave, leading in turn to an increase in the spatial extent of the zone of nutritional deficiency. However, the stratigraphic distribution of cavernicolous bivalve assemblages within the cave requires additional consideration, as the possibility exists that the lowest part of the cored sediments consists of sediment gravity flow deposits (22 cm thick), which would have modified the species composition in the sediments (see below). To extend Kitamura et al.'s (2007a) study, we examined the temporal distribution of both cavernicolous bivalves and sediment within Daidokutsu cave during the past 7,000 years, based on an examination of newly obtained sediment cores.

Study area~~—~~

Cave conditions and sediments

Ie island is approximately 23 km^2 in area and is covered by the Pleistocene Ryukyu Limestone, with a fringing reef close to Pleistocene limestone sea cliffs that ~~have been~~are undercut at the mean high-water level (Fig. 1). The surface of the fringing reef

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80 is largely flat and is exposed at ebb tide (mean tidal range, 1.8 m). The reef crest is

81 located roughly 200 m from the shoreline, and 20 m from the entrance to Daidokutsu

82 cave.

83   Daidokutsu cave is situated on the northeastern coast of Ie Island. The cave's

84 entrance lies at approximately 19 m below sea level (Fig. 1), and is roughly 2 m high

85 and 18 m wide (Hayami and Kase 1992). The cave is 40 m long, dark inside, and

86 deepens abruptly inward to its deepest point at 29 m below sea level. Water temperature

87 within the cave ranges from 30°C (August) to 20°C (February), and seasonal trends in

88 water temperature are similar to those at 30 m water depth in the open ocean around

89 Okinawa (Kitamura et al. 2007b). During sediment sampling, Wwe found air bubbles

90 rising from the sea floor above the cave during sediment sampling, indicating that water

91 is exchanged between the water masses inside and outside the cave via the cave

92 entrance and via numerous passages in the surrounding porous substrates.

93   Based on the sea-level curves of Fairbanks (1989), Bard et al. (1996), and Toscano

94 and Macintyre (2003), Daidokutsu cave is considered to have become submerged at ca.

95 9,000 yr BP, with the entrance having become completely submerged at about 8,000 yr

96 BP. Sea level had attained its present level by about 7,000 yr BP.

97   The floor of the cave is covered by calcareous sediments (Kitamura et al. 2003).

98 Kitamura et al. (2007a) divided the surface sediments in the cave into three facies (Fig.

99 2): Facies 1 is gray calcareous sand that occurs at sites close to the entrance, Facies 2 is

100 gray calcareous mud that occurs in the inner part of the cave, and Facies 3 is calcareous

101 sand containing the skeletons of partly encrusted coralline sponges, which occurs in

102 patches within Facies 2.

103   Kitamura et al. (2007a) collected and examined cored sediment samples from the

104 central part (core 06) and the innermost part (core 04) of Daidokutsu cave (Figs. 2, 3).

105 Core 06 (148 cm thick) can be divided into a lower part, consisting of yellow

106 calcareous mud (> 22 cm long), and an upper part consisting of gray calcareous mud

107 (approximately 126 cm thick) (Fig. 3). The sharp boundary that separates the two parts

108 is estimated to represent an age of 5,450 cal BP (Kitamura et al. 2007a). Based on the

109 relationship between sediment depth and ^{14}C data, the gray calcareous mud is

110 interpreted to have been deposited continuously at a sedimentation rate of 21.1

111 cm/1,000 years. The ^{14}C ages of samples obtained from the lower part of the core fall

112 within a narrow range from 5,980 to 5,060 cal BP, showing a non-linear relationship

113 with depth (Fig. 3). Accordingly, Kitamura et al. (2007a) considered the possibility that

114 the sediment in the lower part originated as a sediment gravity flow. Although there

115 exist differences in color and sedimentation rate between the yellow and gray

116 calcareous muds, the continuous deposition of mud-sized particles throughout the

117 sequence indicates that still-water conditions prevailed for 5,000 years.

118

119 Bivalve assemblages

120 Hayami and Kase (1992, 1993, 1996) and Kase and Hayami (1992) studied

121 cavernicolous bivalves in tropical west-Pacific coral reefs, including Daidokutsu cave.

122 The authors reported about 60 species of cavernicolous bivalves that share the

123 following common characteristics: 1) reduced adult size (usually less than 5 mm in

124 length); 2) unusually large prodissoconch I and absence of prodissoconch II in many

125 species, indicating non-planktotrophic development; and 3) persistent denticles of the

126 provinculum are retained until the adult stage in many pteriomorph species, indicating

127 significant paedomorphosis by progenesis. According to Kase and Hayami (1992) and

128 Hayami and Kase (1996), these features are regarded to reflect a common adaptive

129 strategy toward the oligotrophic condition and low predation pressure of cave habitats.

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130   Eight bivalve species are dominant in the surface sediments within Daidokutsu cave.

131   Kitamura et al. (2007a) divided these species into three groups based on their spatial

132   distribution (Fig. 4). The first group (*Cosa kinjoi* and *Parvamussium crypticum*) mainly

133   inhabits the innermost cave area, whereas the second group (*Cosa waikikia* and *Hiatella*

134   sp. aff. *H. orientalis*) is found near the entrance, and the third group (*Chlamydella*

135   *tenuissima*, *Cyclopecten ryukyuensis*, and *Carditella iejimensis*) shows no distinct

136   distribution pattern. *Carditella iejimensis* appears to be endemic to caves of Ie Island,

137   while the others are found on many isolated islands in tropical west-Pacific coral reefs

138   (Hayami and Kase 1996).

139   The first group showed a rapid increase in abundance immediately above the

140   boundary between the yellow and gray calcareous muds (ca. 5,450 cal BP) in the

141   central area (core 06; Fig. 3). It is possible that the stratigraphic distribution of this

142   group was influenced by the mixing of shells transported by a sediment gravity flow.

143   The species of the second group, along with *Chlamydella tenuissima*, show a decrease

144   in abundance at about 2,200 cal BP in the central part of the cave (core 06), and the

145   relative abundances of these species are very low in the innermost part of the cave (core

146   04; Fig. 3) over the past 3,000 years. We observed no significant changes in the

147   temporal or spatial distribution of *Cyclopecten ryukyuensis* and *Carditella iejimensis*.

148   These findings indicate that the cave environment has remained largely unchanged for

149   the past 5,000 years.

150

151   **Methods**

152

153   We sampled the cave sediment by hand using a coring tube of 6 cm in diameter and

154   233 cm in length (core 19; Figs. 2, 5). The core did not reach basement. The sediment

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155 core was first split and described, and then sliced into 1 cm thick samples for the

156 measurement of mud and carbonate content. We picked and counted all micro-bivalves

157 from the >0.5 mm fraction of each sample. Mud content was determined using

158 standard sieves. The carbonate content of 500 mg of sediment was determined by

159 gentle removal with 10% acetic acid.

160 Kitamura et al. (2006) reported a pumice-bearing sediment layer (Daidokutsu

161 pumice) within the gray calcareous mud. The main period of deposition of this layer is

162 estimated to have occurred from 1,990 to 1,710 cal BP (Kitamura et al. 2006). The

163 pumice layer can be identified by its relatively low carbonate content, thereby enabling

164 its use as a reference time surface.

165 The obtained bivalves show excellent preservation despite most being

166 disarticulated: the prodissoconch can be observed in many individuals. These factors

167 indicate that the shells represent a life assemblage. Taxonomic identifications are based

168 on Hayami and Kase (1993). For disarticulated shells, a separate valve was counted as

169 one individual. The stratigraphic distribution of each species is expressed as the density

170 of individuals (numbers per gram).

171 The radiocarbon ages of three well-preserved mollusc shells were determined by

172 Beta Analytic Inc., using accelerator mass spectrometry (Table 1). Calibrated age

173 ranges were calculated according to Method A of Stuiver et al. (1998) after applying a

174 local correction for the northwestern Pacific of 355 years ($\Delta R = 35 \pm 25$) (Hideshima et

175 al. 2001).

176 In this study, we discovered sand-sized brown grains (debris derived from a red soil

177 layer; see below) in the lower portion of core 19. We observed these grains in thin

178 sections viewed under a polarizing microscope, and analyzed their mineral composition

179 by powder X-ray diffractometry (XRD) using a Rigaku RINT2500 V housed at

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Shizuoka University, Japan. The major element compositions of ~~ten~~ 10 brown grains were analyzed ~~by~~using a non-destructive energy dispersive ~~type~~ X-ray fluorescence (XRF) analyzer~~,~~ (TATSCAN-F1) housed at the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). The chemical compositions were determined at a tube voltage of 30kV and the diameter of the collimater was 400μm. We picked and counted all brown grains from the 0.5-1.0 mm and 1.0-2.0 mm fractions of samples collected at 1 cm ~~thick~~ intervals ~~from~~ within core 19. In the same way, we determined the stratigraphic distribution of brown grains in cores 04 and 06. We also picked and counted brown grains from the 0.5-1.0 mm and 1.0-2.0 mm fractions of a sample of reef-slope sediment and six samples of surface sediment from within the cave (Figs. 1, 2).

Results

The sediment in core 19 shows a fining-upward trend, and is divided into a lower gray calcareous sand (233-178 cm depth) and an upper gray calcareous mud (178-0 cm depth) (Fig. 5). Between 233 and 192 cm depth, the carbonate content increases upward from 88 to 94%. Except for the horizon from 52 to 28 cm depth, the carbonate content between 192 and 0 cm depth is consistent at 95-97%. Between 52 and 28 cm depth, the carbonate content decreases to 84% (Fig. 5). We regard this horizon to represent the deposit containing the Daidokutsu pumice (deposited between 1,990 and 1,710 cal BP).

Table 1 lists the radiocarbon ages obtained for mollusc shells; ^{14}C ages are plotted in Fig. 5. The age of a bivalve shell from the base of core 19 is 7,170 ± 45 cal BP, indicating that the cored sediments preserve a record of fossils and sedimentation over the past 7,000 years. Based on ^{14}C age data and the stratigraphic position of the

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205 Daidokutsu pumice, we estimate a sedimentation rate of 41.7 cm/1,000 years between

206 150 and 233 cm depth, and a rate of 29.8 cm/1,000 years between 0 and 150 cm depth

207 (Fig. 5). This change in sedimentation rate at 150 cm depth was synchronous with the

208 change in deposition from calcareous sand to calcareous mud. An age-depth model

209 presented in this study reveals that pale yellow calcareous mud of in the lower part of

210 core 6 is heteropic with gray calcareous mud of in core 19 (Figs. 3, 5), although we

211 cannot explain the cause of the change in sediment color at ca. 5,450 cal BP.

212   Observations of thin sections reveal that the sand-sized brown grains are also brown

213 internally (Supplementary Fig. 1). The grains were not dissolved by 10% acetic acid,

214 and XRD analysis reveals that they contain quartz (Fig. 6). XRF analysis reveals that

215 the grains consist mainly of Si, Al, and Fe (Table 2). Based on these observations, we

216 interpret that the brown grains are to be detritus derived from a red soil layer that are is

217 widely distributed across Ie Island (Tokashiki 1993; Vuai et al. 2003; Mkadam et al.

218 2006). The dDebris with a diameter of 1.0-2.0 mm in diameter was only found from in

219 the lower part of core 19 (Fig. 5). The number density of these grains (numbers per

220 gram) decreases upward from 0.6/g at 233 cm depth to 0-0.1/g at 203 cm depth. The

221 number density of debris with a diameter of 0.5-1.0 mm shows an upward in diameter

222 decreases upward from 10/g at 233 cm depth to 0-1/g at 180 cm depth (Fig. 5). This

223 upper stratigraphic limit of small-sized debris (0.5-1.0 mm in diameter) derived from

224 the red soil layer coincides with the boundary between calcareous sand and calcareous

225 mud (178 cm depth), and coincides with an upward increase in carbonate content over

226 the interval between 233 and 192 cm depth. The debris from the red soil layer is

227 recognized within surface sediment at three sites (d-f) of the six sites analyzed in the

228 cave, although at number densities less than 0.08/g (Table 3). We found no the debris at

229 the other three sites (a-c) in the cave, in the reef-slope sample (Table 3), or in core 04.

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230 The debris occurs sporadically in core 06 (Fig. 3).

231   The cavernicolous bivalve fauna within core 19 is dominated by *Huxleyia*

232 *cavernicola*, *Bentharca tenuis*, *Cosa kinjoi*, *Cosa waikikia*, *Parvamussium crypticum*,

233 *Cyclopecten ryukyuensis*, *Chlamydella tenuissima*, *Carditella iejimensis*, and *Hiatella*

234 sp. aff. *H. orientalis* (Fig. 5, Supplementary Table 1). Species of the first group (*Cosa*

235 *kinjoi* and *Parvamussium crypticum*) occur continuously above 158 and 130 cm depth,

236 respectively. In contrast, species of the second group (*Cosa waikikia* and *Hiatella* sp.

237 aff. *H. orientalis*) show an upward decrease in abundance ~~at~~ from about 72 cm depth.

238 The stratigraphic distribution of *Chlamydella tenuissima* and *Bentharca tenuis* is

239 similar to that of the second group. *Huxleyia cavernicola* ~~showed~~ shows an upward

240 decrease in abundance ~~at~~ from about 150 cm depth. Both *Cyclopecten ryukyuensis* and

241 *Carditella iejimensis* occur continuously throughout the cored sediments (Fig. 5).

242

243 **Discussion**

244 Debris from the red soil layer

245 In ~~this study~~core 19, ~~we found that~~ debris from the red soil layer is commonly observed

246 in the horizon from the bottom of the core ~~19~~ to about 180 cm depth. The age range of

247 this interval is estimated to be ~~between~~ 7,000 ~~and~~ to 6,000 cal BP, based on our age

248 model (Fig. 5). In contrast, the debris ~~was~~ is only rarely observed in the younger

249 sediments ~~of~~ within core 19, in other cores (04 and 06), and in surface sediments

250 sampled from within the cave, and ~~was~~ is absent from reef-slope sediments (Table 3).

251 Consequently, we consider that the stratigraphic distribution of debris from the red soil

252 layer indicates that the washing of debris from coastal paleosols became weaker, and

253 nearly terminated, during the period leading up to 6,000 cal BP.

254   Kawana and Kan (2002) reconstructed the Holocene development of coral reefs

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around southern Okinawa Island, located about 70 km south of the present study area, based on an analysis of drilling cores. The authors documented that reef began to grow upward upon basement at about 7,600 yr BP, under 10-20 m water depth, and reached the present sea surface at 6,000-5,500 yr BP, and then developed seaward by via accretion of the forereef. At the time when a similar pattern of coral reef development occurred around Ie Island, the termination of the supply of debris from the red soil layer coincided with the establishment of the reef crest/flat zones (when the reef reached the present sea level). The observed changes in supply of debris from the red soil layer are therefore considered to be consistent with the existence of a high-energy window—a concept first proposed by Neumann (1972) and revisited by Hopley (1984). During the mid-Holocene, in areas where the rate of sea-level rise outstripped the ability of newly settled coral communities to grow vertically, a period of high wave energy may have occurred prior to the formation of a reefal barrier. The high-energy window may have remained open from the first complete submergence of the antecedent foundations until the moment at which modern reef flats began to develop, between about 8,000 and 6,000 yr BP (Neumann, 1972; Hopley, 1984; Montaggioni, 2005). Under such conditions, the enhanced hydrodynamic energy may have helped resulted in the rapid winnowing of finer particles from paleosols and terrigenous sediments deposited on inner shelves and coastal zones. From 6,000 yr BP, the window progressively closed as reef tops reached the sea level, which stabilized around its present position, and reef flats became sufficiently extended laterally. Consequently, the supply of detritus was terminated. It appears that the stratigraphic distribution of debris from the red soil layer provides direct evidence of the occurrence of athe mid-Holocene high-energy window.

It is noteworthy that the decline in the abundance of larger debris (1.0-2.0 mm in diameter) preceded that of smaller debris (0.5-1.0 mm in diameter) by 550 years (Fig.

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280   5). This difference is well explained by a weakening in water flow within the cave,

281   rather than changes in sorting processes outside the cave.

282

283   Long-term changes in cavernicolous bivalve assemblages

284   The continuous occurrence of *Cyclopecten ryukyuensis* and *Carditella iejimensis*

285   indicates that the cave environment in Daidokutsu has persisted for the past 7,000 years.

286   The progressive decrease in abundance of species of the second- group (*Cosa waikikia*

287   and *Hiatella* sp. aff. *H. orientalis*), as well as *Chlamydella tenuissima* and *Bentharca*

288   *tenuis*, is consistent with the findings of Kitamura et al. (2007a). Our data indicate that

289   species of the first -group (*Cosa kinjoi* and *Parvamussium crypticum*) were absent from

290   core 19 at depths between 223 and 160 cm, although other species occurred

291   continuously throughout this interval. This finding confirms Kitamura et al's (2007a)

292   tentative conclusion that spiecies of the first -group species living in the innermost part

293   of the cave became dominant over the past 5,000 years. In addition, we found that

294   *Huxleyia cavernicola* shows an upward decrease in abundance fromat a depth of about

295   150 cm, corresponding to about 5,130 cal BP. The bivalve species described above are

296   suspension feeders, whereas *Huxleyia cavernicola* is thought to be a deposit feeder

297   (Hayami and Kase 1993). This species is very rare in the surface sediments in the cave

298   (Fig. 4). Thus, the temporal changes in species abundance reveal that a decrease in the

299   amount of organic matter in cave sediment decreased at about 5,130 cal BP.

300   As noted above, our new data indicate that the water flow in the cave weakened at

301   about 6,500 cal BP, suggesting in turn a decrease in the exchange of water between the

302   interior and exterior of the cave, and a consequently a decline in nutrient levels within

303   the cave. However, the observed changes in cavernicolous bivalve assemblages

304   occurred after termination of the supply of debris from the red soil layer, at about 6,000

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cal BP. This finding indicates that the population dynamics of *Cosa waikikia*, *Hiatella* sp. aff. *H. orientalis*, *Chlamydella tenuissima*, *Bentharca tenuis* and *Huxleyia cavernicola* were not significantly influenced by the decline in nutrient supply at about 6,500 cal BP. However, it ~~seems~~ appears that the ongoing decline in nutrient supply resulted in an expansion of the distribution of *Cosa kinjoi* and *Parvamussium crypticum*, thereby preventing the five species listed above from inhabiting the inner part of the cave.

The large extent of the cryptic habitat and extensive cover of encrusting organisms within reef cavities provide a potentially important interface in the exchange of material between cavities and the overlying water column (e.g., Tribble et al. 1988; Richter and Wunsch 1999). Coral cavities are sinks of bacterioplankton and dissolved organic carbon, and a source of NO_x and PO_4^{3-} (Van Duyl et al. 2006; De Goeij and Van Duyl 2007; De Goeij et al. 2008). Our results show that, at least in terms of the coral cryptic community within cavities developed in the reefal foundations, ~~the~~ a decline in the functioning of the cryptic community as a source of nutrients to the coral reef ~~has continued~~ over at least the past 6,500 years.

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457

458   Figure captions

459   Figure 1 Location map of the submarine Daidokutsu cave on Ie Island, off Okinawa

460   Island, Japan.

461

462   Figure 2 Map showing water depth and the locations of sampling points of surface

463   sediments (a-f) and cored sediments. Also shown is the distribution of surface

464   sediment facies (see text for details).

465

466   Figure 3 Columnar sections of submarine-cave sediment within cores 04 and 06,

467   showing stratigraphic changes in mud and carbonate content, abundance of debris

468   derived from a red soil layer, the dominant cavernicolous bivalve species, and

469   depositional rates, as inferred from the ^{14}C ages of molluscs (modified after

470   Kitamura et al. 2007a).

471

472   Figure 4 Spatial distributions of selected cavernicolous bivalve species in Daidokutsu

473   cave (modified after Kitamura et al. 2007a). Percentages are given relative to the

474   total number of individuals of all bivalve species. The locations of a-f are shown in

475   Fig. 2.

476

477   Figure 5 Columnar sections of submarine-cave sediment within core 19, showing

478   stratigraphic changes in mud and carbonate content, abundance of debris derived

479   from a red soil layer, the dominant cavernicolous bivalve species, and depositional

480   rates, as inferred from the ^{14}C ages of mollusks.

481

482   Figure 6 Diffractograms of brown grains (debris derived from a red soil layer) found

21

483　　within sediments from Daidokutsu cave. Peaks labelled "1" correspond to those

484　　peaks for quartz.

485

486　Table 1 Results of ^{14}C dating of molluscs. All samples were analyzed by accelerator

487　　mass spectrometry.

488

489　Table 2 Concentrations of major elements (wt%) within 10 grains of debris derived

490　　from a red soil layer, as measured by non-destructive X-ray fluorescence.

491

492　Table 3 Grain distribution (wt%) and number density of debris derived from a red soil

493　　layer (number/g) in a sample of reef-slope sediment and six samples of surface

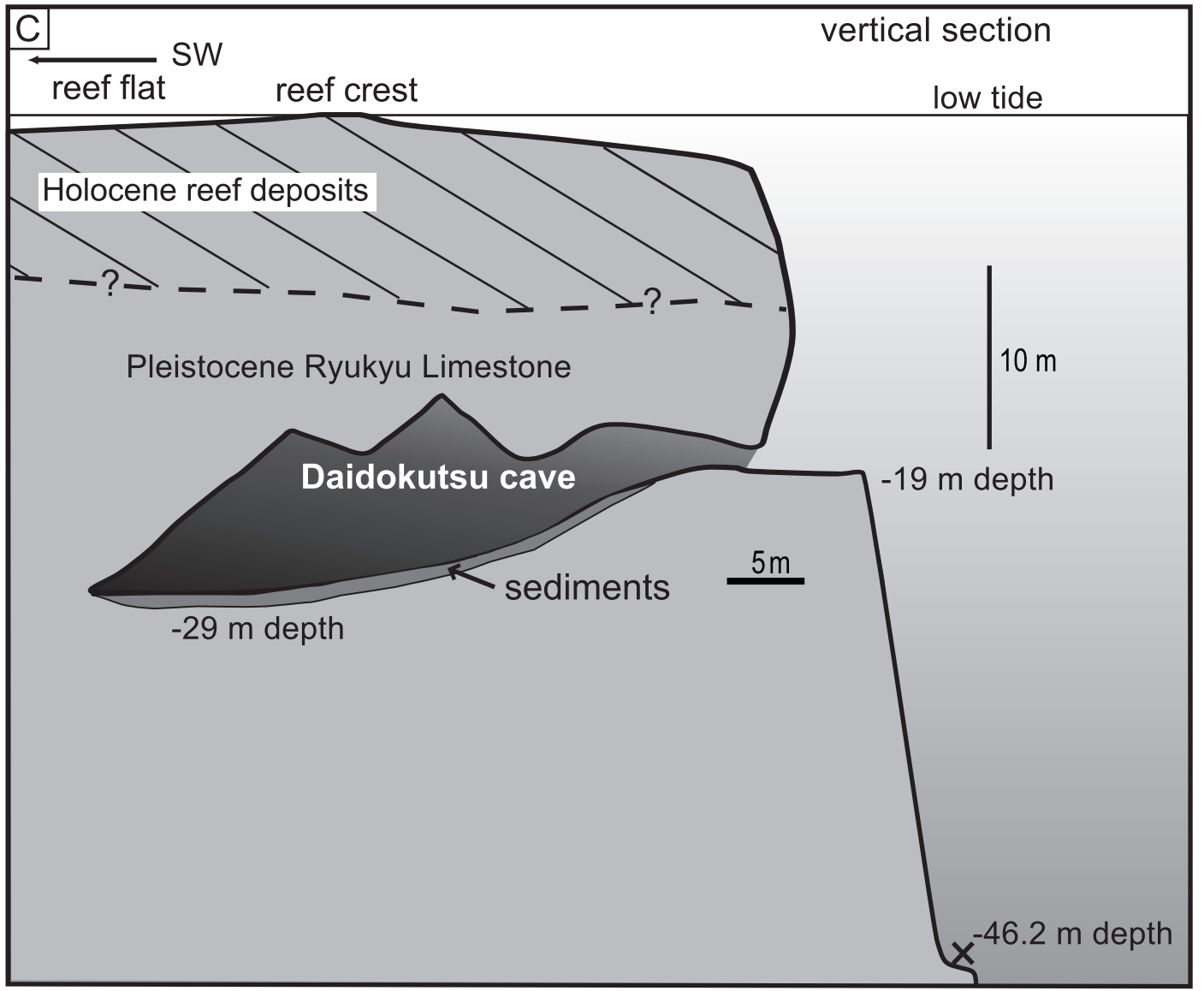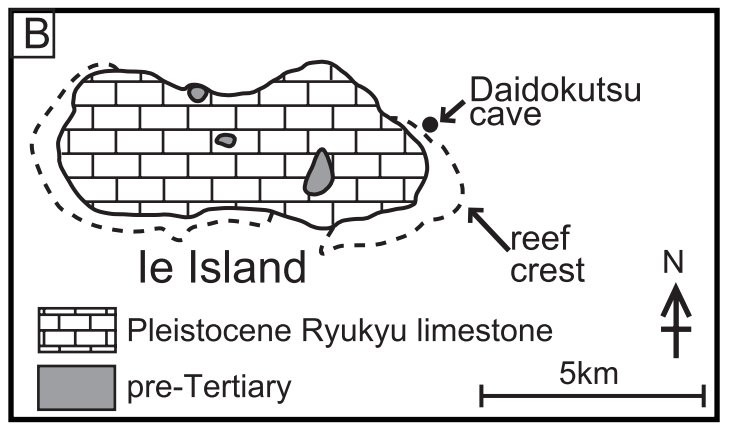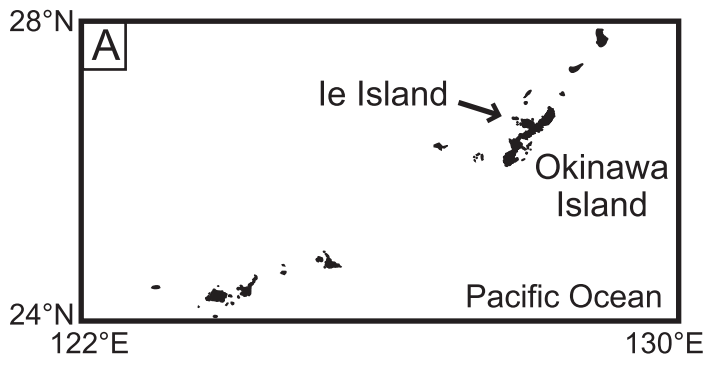494　　sediment from within Daidokutsu cave.

495

496　Electronic Supplementary Material Figure 1 Photomicrographs of debris derived from a

497　　red soil layer (plane-polarized light).

498

499　Electronic Supplementary Material Table 1 List of cavernicolous bivalve species in

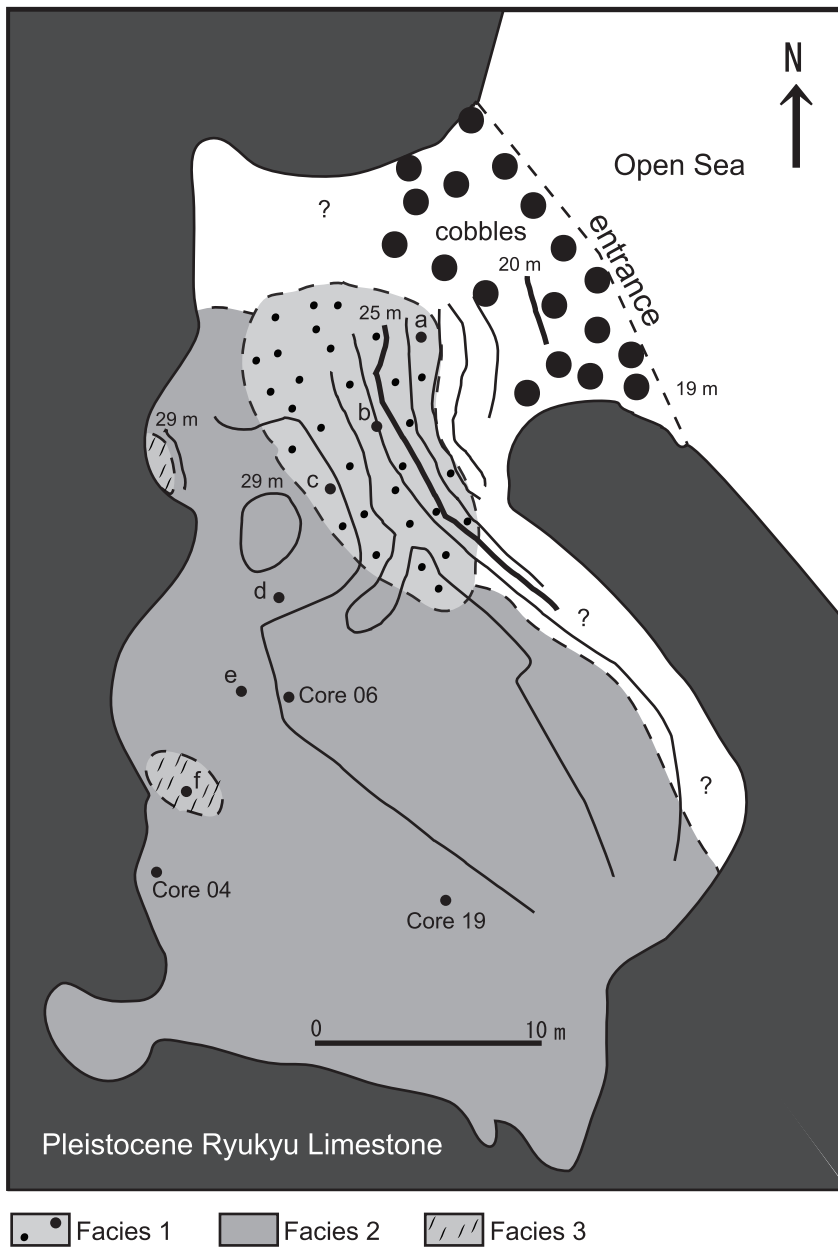500　　core 19. A: articulated shells, R: right valve, L: left valve.

A

28°N
24°N
122°E 130°E

Ie Island
Okinawa Island
Pacific Ocean

B

Daidokutsu cave
Ie Island
reef crest
N

Pleistocene Ryukyu limestone
pre-Tertiary
5km

C

vertical section
SW
reef flat
reef crest
low tide

Holocene reef deposits
-?-
?
Pleistocene Ryukyu Limestone

10 m

-19 m depth

Daidokutsu cave
sediments

5m

-29 m depth

-46.2 m depth
×

× sampling point of reef slope sediment

Yamamoto et al Fig. 1

N

Open Sea

?

cobbles

20 m

entrance

25 m

a

19 m

29 m

29 m

b

c

d

?

e

Core 06

f

?

Core 04

Core 19

0   10 m

Pleistocene Ryukyu Limestone

Facies 1   Facies 2   Facies 3

Yamamoto et al. Figure 2

Yamamoto et al. Fig. 3

1st group

Cosa kinjoi

Parvamussium crypticum

2nd group

Cosa waikikia

Hiatella sp. aff. *H. orientalis*

3rd group

Cyclopecten ryukyuensis

Chlamydella tenuissima

Carditella iejimensis

Huxleyia cavernicola
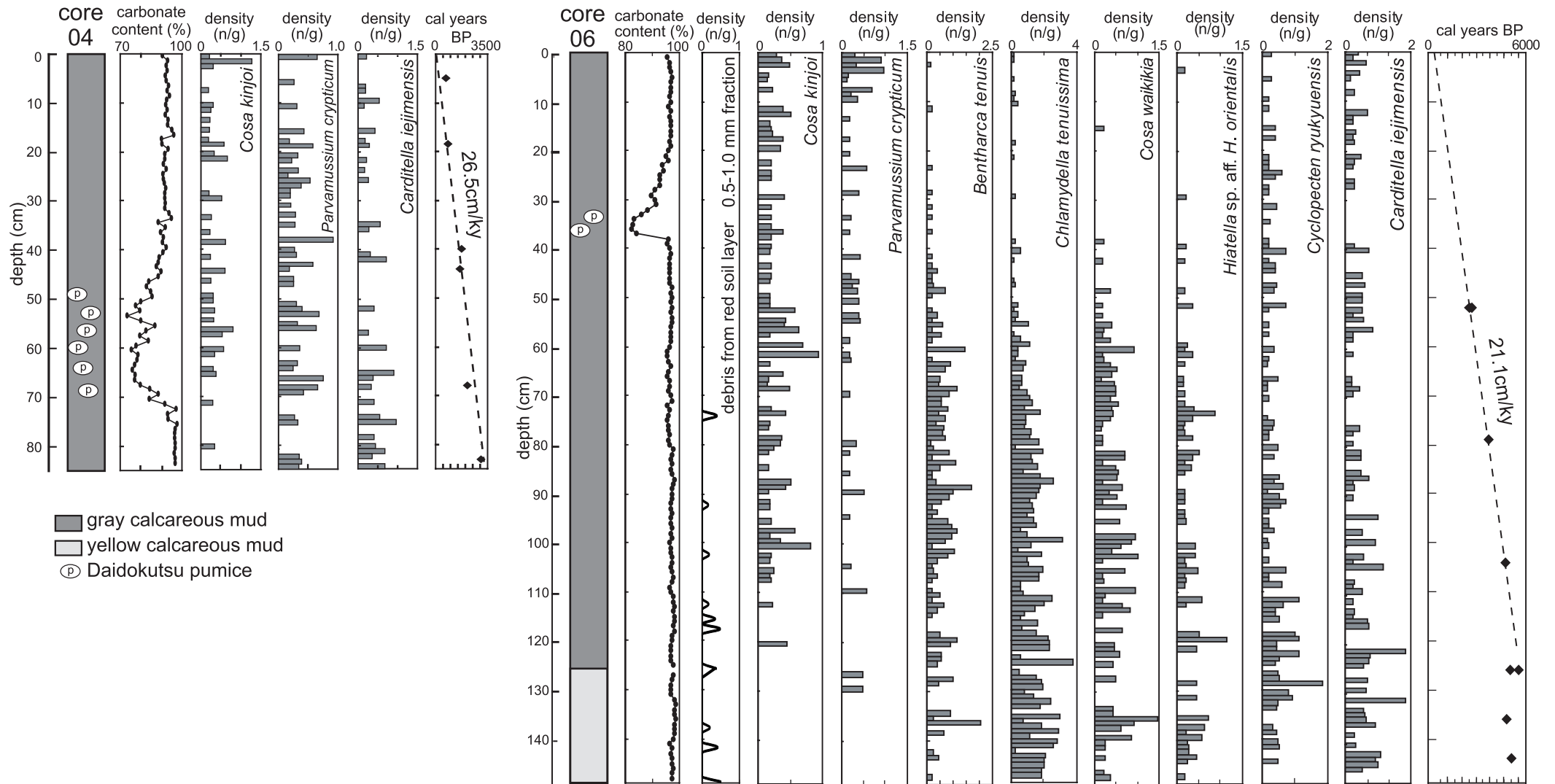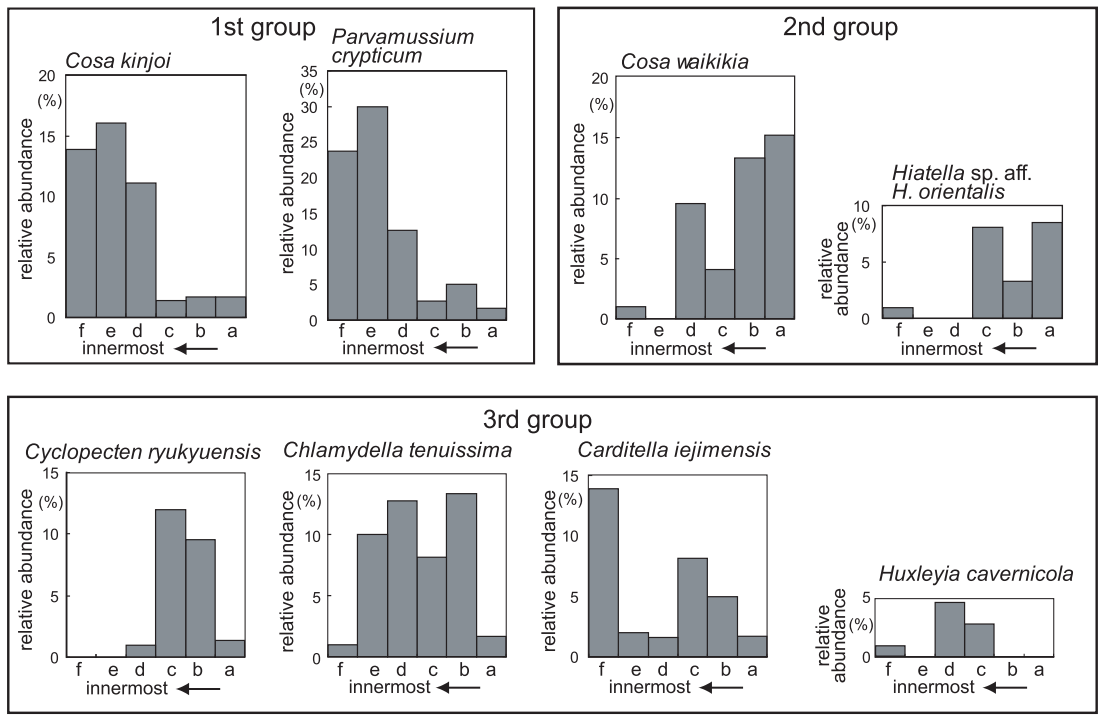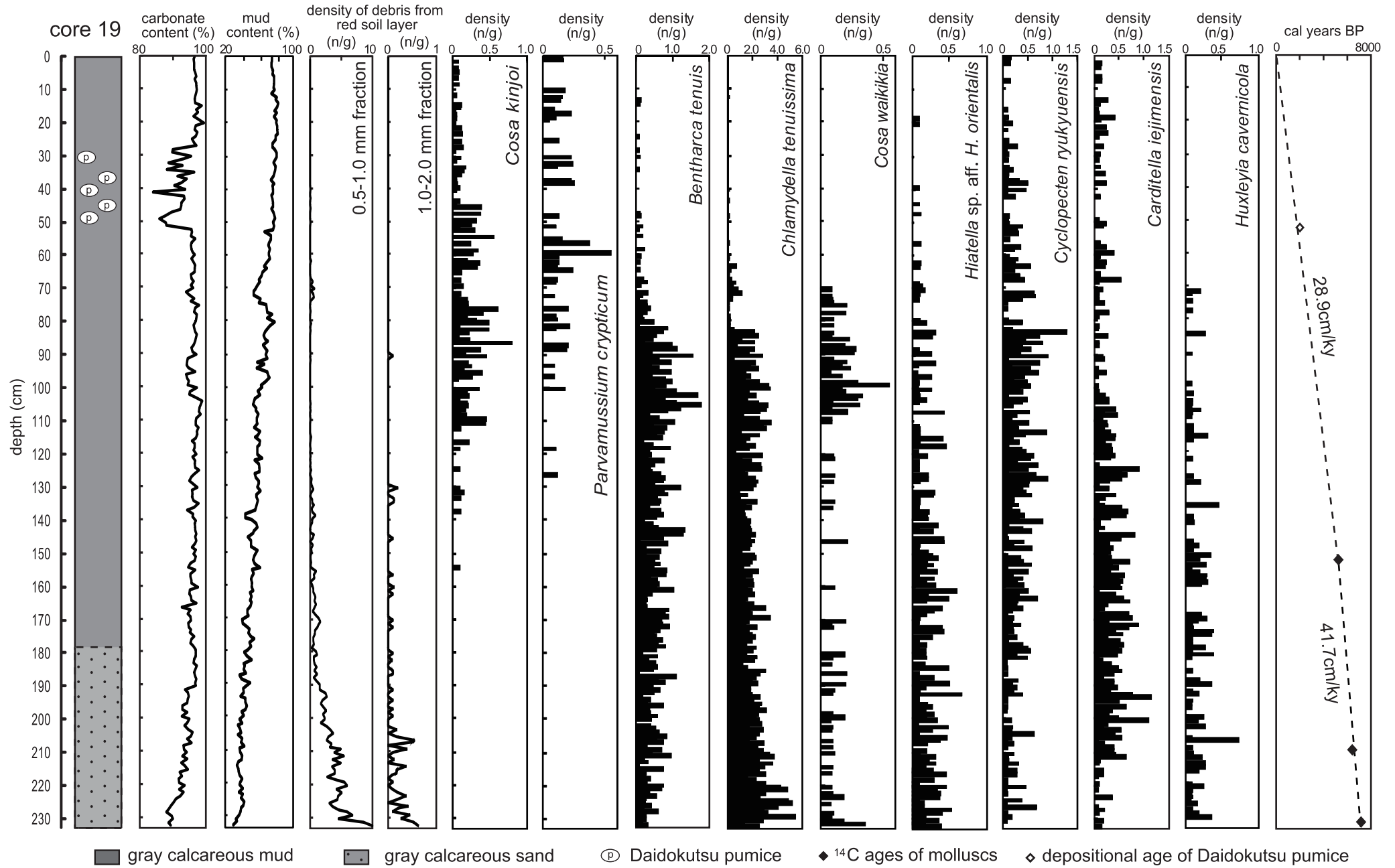
Yamamoto et al. Fig. 4

Yamamoto et al. Fig 5

depth (cm)	laboratory number	sample	preservation	measured ^{14}C age (BP)	δ^{13}C	conventional ^{14}C age* (BP)	Calibrated age	
							intercept** (cal BP)	age ranges (cal BP)
153	Beta-241526	*Acar congenita*	articulated shell very good	4430 ± 40	+3.3	4890 ± 40	5220	5270-5060
211	Beta-236980	*Barbatia cometa*	disarticulated shell very good	5590 ± 40	+2.2	6040 ± 40	6400	6460-6370
233	Beta-236979	*Indocrassatella oblongata*	disarticulated shell very good	6240 ± 40	+1.7	6680 ± 40	7170	7230-7140

*reservoir correction was not applied.

**intercepts between the conventional ^{14}C age and the calibration curve of Stuiver *et al*. (1998).
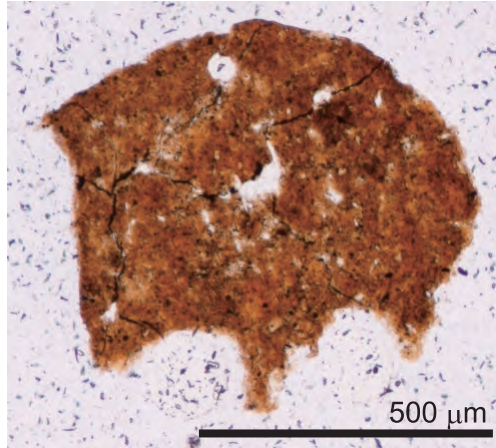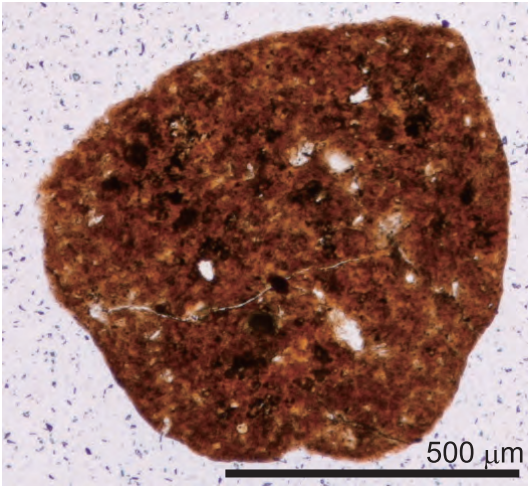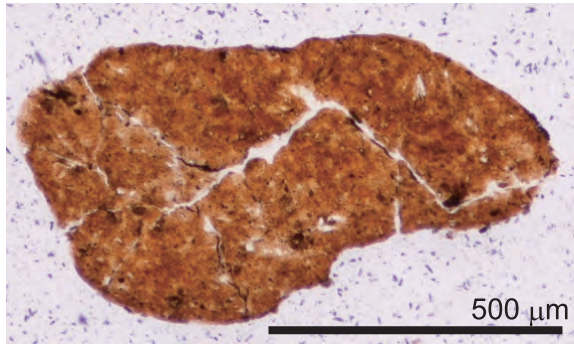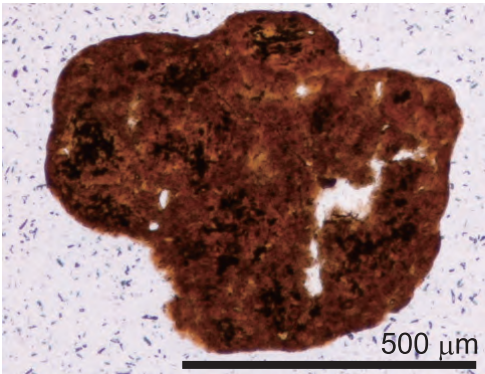
All errors are 1σ.
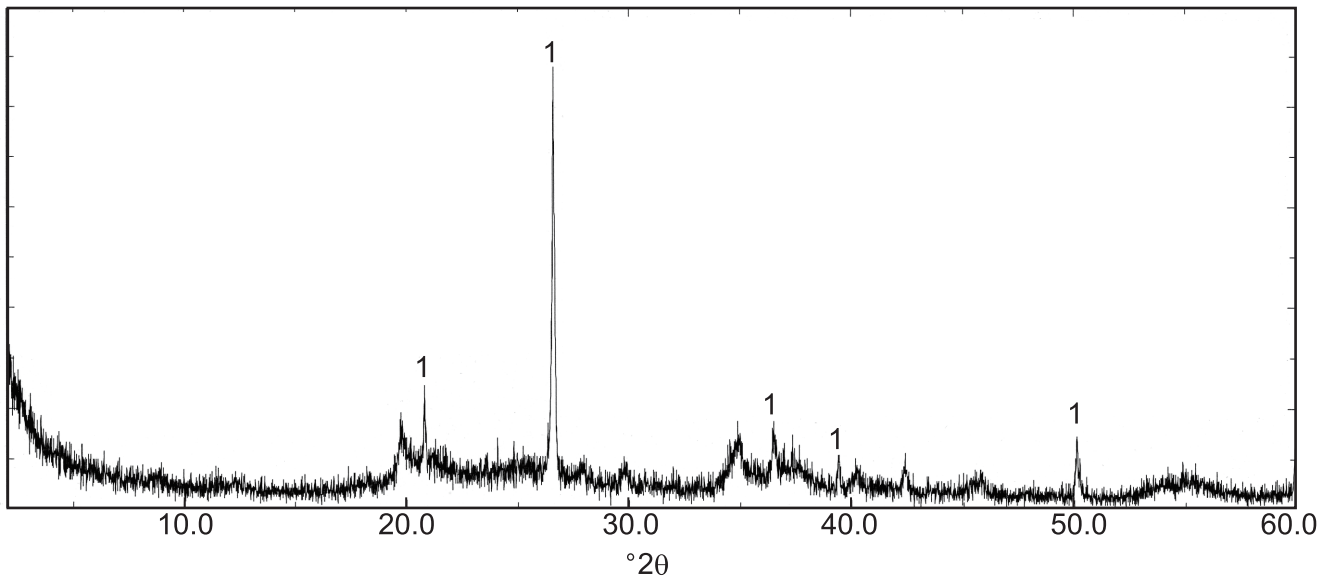
Yamamoto et al. Fig 6

Sample no.	1	2	3	4	5	6	7	8	9	10
Mg	3.5	4.9	6.2	5.8	9.4	7.8	5.0	3.3	5.9	7.3
Al	19.5	18.4	22.5	18.3	17.5	21.6	17.5	24.6	18.2	20.5
Si	51.2	51.1	41.6	40.6	33.6	39.0	43.7	37.7	38.5	38.3
K	6.8	6.5	7.0	5.3	4.7	5.5	6.4	5.9	4.6	5.3
Ca	2.0	0.8	1.8	3.7	4.2	0.9	5.0	1.8	0.7	1.5
Ti	2.5	2.2	1.8	1.9	1.2	1.3	2.3	2.1	1.3	1.6
Fe	14.0	15.7	18.7	22.5	27.6	22.8	19.5	23.4	29.9	24.7
others	0.5	0.4	0.4	1.9	1.8	1.1	0.6	1.2	0.9	0.8

Sample	grain distribution (ϕ)											lateritized debris
	<-4	-4~-3	-3~-2	-2~-1	-1~0	0~1	1~2	2~3	3~4	4~5	>5	
reef slope	0.0	0.0	0.0	0.0	2.1	7.0	39.3	36.7	10.6	0.9	3.4	0.00
a	0.0	0.0	6.2	9.4	14.6	18.6	21.0	12.4	5.9	3.4	8.3	0.00
b	0.0	1.7	10.5	10.0	16.7	15.5	13.0	7.3	6.1	7.3	11.7	0.00
c	0.0	0.0	0.0	0.0	10.0	16.0	32.9	18.4	5.9	5.9	10.8	0.00
d	0.0	0.0	0.0	0.0	2.3	1.9	4.0	5.6	13.3	27.6	45.2	0.04
e	0.0	0.0	0.0	0.0	1.4	1.7	3.6	7.5	16.0	30.3	39.3	0.04
f	0.0	19.0	4.7	5.7	5.1	5.3	10.6	12.6	14.3	11.3	11.3	0.08

500 μm

500 μm

500 μm

500 μm

Yamamoto et al, Suplpementary Material Figure 1