Biostratigraphy, geochronology and sedimentation rates of the upper Miocene Pisco Formation at two important marine vertebrate fossil-bearing sites of southern Peru

Karen Gariboldi[a,b,c], Giulia Bosio[c], Elisa Malinverno[c], Anna Gioncada[a], Claudio Di Celma[d], Igor M. Villa[e,f], Mario Urbina[g] and Giovanni Bianucci[a].

a Dipartimento di Scienze della Terra, Università di Pisa, via Santa Maria 53, 56126, Pisa, Italy; karen.gariboldi@for.unipi.it; anna.gioncada@unipi.it; giovanni.bianucci@unipi.it.

b Dottorato Regionale Toscano di Scienze della Terra, Dipartimento di Scienze della Terra, Università di Pisa, via Santa Maria 53, 56126, Pisa, Italy.

c Dipartimento di Scienze dell'Ambiente e del Territorio e di Scienze della Terra (DISAT), Sezione di Scienze Geologiche e Geotecnologie, Università degli Studi di Milano-Bicocca, Piazza della Scienza 4, 20126 Milano, Italy; g.bosio1@campus.unimib.it; elisa.malinverno@unimib.it.

d Scuola di Scienze e Tecnologie, Università di Camerino, Via Gentile III da Varano 1, Camerino, 62032, Macerata, Italy; claudio.dicelma@unicam.it.

e Institut für Geologie, Universität Bern, Baltzerstrasse 3, 3012 Bern, Switzerland; igor.villa@geo.unibe.ch.

f Centro Universitario Datazioni e Archeometria, Università degli Studi di Milano-Bicocca, Piazza della Scienza 4, 20126 Milano, Italy.

g Departamento de Paleontologia de Vertebrados, Museo de Historia Natural-UNMSM, Avenida Arenales 1256, Jesús María, Lima, 14, Peru; mariourbina01@hotmail.com.

Corresponding author:
Karen Gariboldi,
karen.gariboldi@for.unipi.it,
Dipartimento di Scienze della Terra,
Università di Pisa, via Santa Maria 53,
56126, Pisa, Italy.
 Tel: +39-050- 2215750;
Fax: +39-050-2210652/3

Abstract

The Mio-Pliocene Pisco Formation, Peru, is a world renowned Konservat-Lagerstätte. Beside its potential in preserving important information on the history of the Pacific Ocean during the Miocene, the Pisco Fm. provides palaeontologists with the unique opportunity to study in detail the evolution of marine vertebrate fauna during the Neogene. Because diatomites are one of the main lithologies of the Pisco Fm., previous authors have hypothesised exceptionally high sedimentation rates related to the deposition of diatom frustules as the main cause leading to the formation of the Lagerstätte. However, sedimentation rates were never calculated. With the perspective to build a solid stratigraphic framework for the whole Pisco Fm., we started to investigate two important fossiliferous sites: Cerro Colorado and Cerro Los Quesos. Within these two areas, measurement of multiple stratigraphic sections combined with extensive field mapping of a number of distinct

40 marker beds was carried out, which allowed a high-resolution correlation and creation of a local

41 lithostratigraphic framework. Integrated tephrostratigraphy, $^{40}Ar/^{39}Ar$ dating and diatom

42 biostratigraphy permitted an accurate chronostratigraphy to be established. Both biostratigraphic

43 and radiometric ages converge to indicate a late Miocene age for the two sites, amending previous

44 attribution of Cerro Colorado and Cerro Los Quesos to the middle Miocene. Age models for the site

45 of Cerro Los Quesos reveal that sedimentation rates are high but in line with those of high-

46 productivity environments, thus invalidating the hypothesis of exceptional sedimentation rates as

47 the main cause for the formation of the Lagerstätte. These results are extremely important also in

48 the perspective of building a complete stratigraphic framework for the Pisco Fm.

49

50 **Keywords:** Pisco Formation, diatom biostratigraphy, tephrostratigraphy, $^{40}Ar/^{39}Ar$ ages, upper

51 Miocene, sedimentation rates.

1. Introduction

The Pisco Formation is a Mio-Pliocene diatomaceous formation and a world renowned Konservat-Lagerstätte cropping out for 300 km along the Peruvian coast, from Pisco to Yauca (Fig. 1A). Its fossil marine vertebrates have been raising the interest of palaeontologists for years. There are numerous papers describing new vertebrate species found in the Pisco Fm. (e.g., Lambert et al. 2008, 2009, 2010 b, 2013, 2014, 2016, in press; Bianucci et al. 2010, 2016a, 2016b, 2016c, and references therein), their ecology (Lambert et al. 2010a, 2014, 2015; Collareta et al. 2015) and taphonomy (Esperante et al. 2008, 2015; Ehret et al. 2009). Most recently, researchers have focused their attention on the possible mechanisms that led to such a well-preserved fossil-rich deposit. A rapid sinking of the carcasses in soft unconsolidated sediment is considered by different authors (Brand et al. 2004; Gariboldi et al. 2015) as a likely mechanism to explain the exceptional preservation of the vertebrate skeletons. Some authors advocated also extremely high sedimentation rates (of one or two orders of magnitude higher than in modern upwelling settings) to explain the formation of the Lagerstätte (Brand et al. 2004; Esperante et al. 2015). We had proposed instead that there are many causes that led to the formation of the Pisco Lagerstätte, one of these being the palaeogeochemical conditions of the sea bottom environment at the time of the carcasses deposition (Gariboldi et al. 2015; Gioncada et al. 2016).

To date, no attempt has been made to calculate the sedimentation rate along measured sections. Throughout this work we will present biostratigraphic and geochronologic data with the aim of calculating sedimentation rates in the Pisco Basin during the deposition of the Pisco Fm.

Different authors have previously dated the Pisco Fm. using different methods, including K/Ar and ^{40}Ar/^{39}Ar ages and diatom, radiolarian and planktonic foraminifera biostratigraphy (see Table 1 for all the references). K/Ar dates, although well positioned along sections, are biased by the low precision of the method, while most of the times ^{40}Ar/^{39}Ar dates are provided without any information about the analytical precision, the measurement error, and the exact stratigraphic position. Generally, ages were used to date individual localities without any attempt to

92 correlatethem. Brand et al. (2011), by identifying different marker beds, were the first to attempt a

93 correlation between different outcrops exposed along the Ica Valley River but they did not provide

94 a precise location for their dating points. Biostratigraphy, mainly based on diatoms (Mertz 1966;

95 Macharè and Fourtanier 1987; Schrader and Ronning 1988, Tsuchi et al. 1988; Koizumi 1992), was

96 also extensively used but many of the bioevents and species used in those works have been

97 thoroughly revised since the 80s (Gariboldi, 2016).

98   In this work, we developed a robust lithostratigraphic framework for two localities where

99 the Pisco Fm. crops out: Cerro Colorado (CC hereafter; Di Celma et al. 2016a) and Cerro Los

100 Quesos (CLQ hereafter; Di Celma et al., 2016b) (Fig. 1B). Stratigraphically complete, composite

101 sediment columns (Fig. 2A, B) were assembled by combining a set of individual measured sections

102 that were laterally correlated in the field by literally walking on the local marker beds. Diatomites

103 and tephra samples were collected along these sections to develop the chronostratigraphic model

104 presented in this work; this is based on new micropalaeontologic data and radiometric (^{40}Ar/^{39}Ar)

105 age determinations. The Pisco Fm. diatom biostratigraphy was revised following most recent

106 publications on Equatorial Pacific diatom biostratigraphy (mostly Barron 2003), although we are

107 aware that a solid calibration of bioevents with magnetostratigraphy/astrochronology in this region

108 is still lacking and would produce more reliable results.

109   Beside the debate on the origin of the Lagerstätte, a high resolution chronostratigraphic

110 framework for the Pisco Fm. is of fundamental importance to reconstruct in detail the evolutionary

111 history of the impressive vertebrate fauna of the Pisco Basin, which has been mapped in detail at

112 CC and CLQ (Bianucci et al. 2016a, 2016b). For example, this work could provide a more precise

113 age constraint for the giant raptorial sperm whale *Livyatan melvillei* of which the holotype and only

114 known specimen was found at CC (Lambert et al. 2010b). This datum would be important, since the

115 appearance of this megapredator could have had a high impact in the marine vertebrate ecosystem.

116

117 **2. Geologic setting**

118

2.1. Stratigraphy

The Cenozoic tectonics of Peru was controlled by the oblique subduction of the eastern edge of the oceanic Nazca Plate underneath the Peruvian portion of the South American plate (e.g., Barazangi and Isacks 1979; Pilger 1981; Cahill and Isacks 1992; Gutscher et al. 2000). The collision of the two plates deformed the leading edge of the South American Plate and developed a composite transform-convergent margin characterised by lateral strike-slip, normal and oblique-slip faults that formed a number of elongated basins along the western margin of Peru (León et al. 2008; Zúñiga-Rivero et al. 2010). The (East) Pisco Basin is one of these fault-bounded basins and its sedimentary fill includes the Eocene Paracas Group (Los Choros and Yumaque Formations), the late early-early late Oligocene Otuma Formation, the late Oligocene-middle Miocene Chilcatay Formation, and the Miocene-Pliocene Pisco Formation (Dunbar et al. 1990; DeVries 1998). These sedimentary packages are bounded by well-defined, regionally traceable angular unconformities recording discrete periods of subaerial exposure. Regional uplift and deep erosion followed in the late Pliocene and Quaternary to reveal the complex interplay between depositional history and tectonic deformation during the evolution of the Basin (León et al. 2008).

The Pisco Fm. is characterised by a wide spatial variability in thickness and sedimentary facies. Previous measurement of sections at different localities led to the subdivision of the Mio-Pliocene Pisco Basin in a north (Pisco area), central (Ica River Valley) and southern (Sacaco) Basin (e.g., Marty 1989, Dunbar et al. 1990). A robust lithostratigraphic framework (Di Celma et al. 2016a, 2016b) and a detailed structural analysis of fault systems (Rustichelli et al. 2016a, b) have been developed at CC and CLQ, some 25 and 50 km south of the Ica town.

At CC, the measured stratigraphy of the Pisco Fm. has been subdivided into two allomembers separated by an intraformational unconformity. The Lower Allomember lies with marked angular unconformity directly on the deformed strata of the underlying Chilcatay Fm. and consists of diatomites, diatomaceous siltstones with minor dolomite horizons and occasional

144 volcanic ash layers, lying on a basal conglomerate and burrow-mottled sandstone beds. The Upper

145 Allomember comprises a basal pebble-bearing interval overlain by a 50 m thick sand-prone

146 package, diatomaceous siltstones and diatomite beds with subordinate volcanic ash layers,

147 sandstone beds and dolomite horizons (Di Celma et al. 2016a).

148 At CLQ, the measured stratigraphy mainly consists of diatomaceous siltstones and diatomites

149 with interbedded ash layers and dolomite layers lying on basal sandstone beds (Di Celma et al.

150 2016a). The CLQ section has been divided into 6 Members (from A to F, Fig. 2B) distinguished on

151 the basis of their characteristic lithofacies (Di Celma et al., 2016b). The intraformational

152 unconformity documented at CC was only recently recognised at CLQ and represents an

153 improvement of Di Celma et al. (2016b). At CLQ it is at about 29 m above the base of the section

154 (abs hereafter) and is marked by a 20 cm thick, laterally discontinuous lag of molluscs, shark teeth

155 and phosphorite nodules. Consequently, also at CLQ the Upper and Lower Allomember identified

156 at CC can be recognised.

157 In general, sedimentary structures and microfossil assemblages suggest that the water depth of

158 the Pisco Basin at the two studied sections ranged between 0 and 100 m (inner-middle shelf), the

159 CC section being characterised by shallower depths than CLQ for most of its development

160 (Gariboldi et al. 2015; Di Celma et al. 2016a, 2016b).

161

162 *2.2. Previous dating*

163

164 As summarised in Table 1, previous authors have dated the Pisco Fm. by means of different

165 methods.

166 K-Ar ages for the Pisco Fm. were first obtained for the Southern Basin (Muizon and Bellon

167 1980; 1986; Muizon and DeVries 1985). They report late Miocene ages of 9.5 Ma (base of El

168 Jahuay section) and 8.8 and 8 Ma (base of Aguada de Loma section) for the basal Pisco Fm. and a

169 Pliocene age of 3.9 Ma (Sacaco section) for the upper Pisco Fm. (supplementary material, Fig. S1).

170   Dunbar et al. (1990) listed K-Ar dates obtained for the Pisco Fm. that range from 6.89 ±

171   0.10 Ma in the northern Basin (Monte Caucato section) to 6.75 ± 0.18 Ma in the central Basin

172   (Queso Grande section) to 5.49 ± 0.12 and 6.42 ± 0.12 Ma in the southern part of the central Basin

173   (Molde de Queso and Huaracangana sections, respectively). New $^{40}Ar/^{39}Ar$ ages are provided by

174   Brand et al. (2011) and Esperante et al. (2015), ranging from 9.2 to 6.85 Ma for different localities

175   in the Ica Valley and from 7.73 to 7.11 for the site of CLQ, respectively (supplementary material,

176   Fig. S1). The stratigraphic position of such dated samples along their composite section is however

177   not well constrained, as stated by the authors (see Brand et al. 2011, Fig. 8).

178   More recently, Ehret et al. (2012) provided ages obtained with Sr isotopic ratio (measured

179   on mollusc shells) and zircon U-Pb dating in the southern Pisco Basin. They report age ranges of

180   9.03-6.51 Ma for the base of El Jahuay section and 8.79-6.45 Ma for the Montemar section; these

181   are compatible with previous K-Ar dates provided for the same sections (Muizon and DeVries

182   1985). Conversely, data obtained by Ehret et al. (2012) on the Sud Sacaco and Sacaco horizons

183   provided ages older than the 3.9 Ma tuff bed of Muizon and Bellon (1980). $^{87}Sr/^{86}Sr$ analysis yield

184   ages spanning from 6.59 Ma to 5.89 Ma for Sacaco and Sud Sacaco, moving those levels from the

185   Pliocene to the late Miocene (see Ehret et al. 2012 for geographic location of the dated sections).

186   Biostratigraphic studies in the literature have been carried out using both macrofauna and

187   microfossils (we report ages of First and Last Occurrences -FO and LO hereafter- preceded by 'ca.'

188   when referring to an uncalibrated age).

189   De Muizon and DeVries (1985) attempted to develop a molluscan biostratigraphy for the

190   uppermost Miocene - lower Pliocene outcrops in the Sacaco area. DeVries (1998) used the

191   molluscan fauna to date the Pisco Basin deposits, considering in particular the occurrence of the

192   bivalve *Anadara sechurana* Olsson, 1932 and of the gastropod *Turritella infracarinata*

193   Grzybowsky, 1899. As *A. sechurana* was considered not younger than middle Miocene, its

194   occurrence was used consequently in following studies to constrain outcrops of the Pisco Fm. (e.g.

195   Bianucci et al. 2010, Fig. S1). However, recent researches highlighted that the range of *A.*

196 *sechurana* is not limited to the middle Miocene and may extend into the early Tortonian. In the

197 Gatun Fm. (Panama), for instance, this species ranges from 11.6 to 10.4 Ma (Austin Hendy personal

198 communication) and its disappearance is likely related to local unfavourable environmental

199 conditions rather than to a real extinction (Austin Hendy personal communication). As such, the use

200 of *A. sechurana* as a reliable biostratigraphic marker for the middle Miocene is questionable.

201 Radiolaria, although sparsely present within silty diatomite and diatomaceous silty layers,

202 provided a well constrained biostratigraphic framework for the Pisco Fm. at different localities of

203 the north, central and south Pisco Basin (Marty 1989, also reported in Dunbar 1990). Biozone

204 assignment identified a latest middle Miocene to early late Miocene interval (*Diarthus pettersonii*

205 zone, 12.02-8.84 Ma following recent calibration for the eastern Equatorial Pacific, i.e. Kamimuri et

206 al., 2009) limited to the north Basin (Monte Caucato section), a middle late Miocene interval

207 (*Didymocyrtis antepenultima* zone, 8.84-7.74 Ma and *D. penultima*, 7.74-6.89 Ma) in some sections

208 of the northern (Monte Caucato section) and central Basin (Cerro Yaparejo, Fundo Santa Rosa,

209 Yesera de Amara sections) and a widespread younger late Miocene to early Pliocene interval

210 (*Stichocorys peregrina* zone, 6.89 – 4.19 Ma) in most sections of the central and southern Basin.

211 Mertz (1966) was the first to describe diatoms from the Pisco Fm.; beside a thorough

212 description of the observed species and a general palaeoecological framework, he also used diatoms

213 to date the Pisco Fm., concluding that it must have been Miocene in age.

214 Macharè and Fourtanier (1987) dated the Pisco Fm. referring to the Equatorial Pacific

215 biostratigraphic scheme of Barron (1983 and 1985) and to the north Pacific biostratigraphic scheme

216 of Akiba (1985) and Akiba and Yanagisawa (1986). The need to use two different schemes resides

217 in the occurrence of species with ranges described in the North Pacific scheme (i.e., *Denticulopsis*

218 *katayamae* Maruyama, 1984 in the Akiba and Yanigasawa North Pacific scheme, 1985) rather than

219 by Barron's 1983 Equatorial Pacific scheme. Basing their conclusions on the ranges of

220 *Coscinodiscus plicatus* Grunow, 1878 and *Denticulopsis hustedtii* (Simonsen and Kanaya, 1961)

221 Simonsen, 1979 (which Macharè and Fourtanier referred to as *Denticula hustedtii*) for the

222 Equatorial Pacific, Macharè and Fourtanier (1987) dated the base of the Pisco Fm. to the middle-

223 late Miocene (14-9 Ma, as reported by the authors). However, they highlight that taking into

224 account the North Pacific range of *D. hustedtii*, the base of the formation would be younger (11-9

225 Ma, as reported by the authors). Notwithstanding the general lack of marker species, they also

226 attributed the middle part of the formation exposed in the southern part of the Basin (Sacaco area,

227 see Plate 1 of Macharè and Fourtanier, 1987 for sample locations) to the late Miocene – early

228 Pliocene, basing their conclusion on the analogies of the association with that of the Sisquoc

229 Formation (California). Finally, they attribute the upper part of the Pisco Fm. to the Pliocene

230 because of the occurrence of *Koizumia tatsunokuchiensis* (Koizumi, 1972) Yanagisawa, 1994

231 (which Macharè and Fourtanier referred to as *Rossiella tatsunokuchiensis*), *Fragilariopsis*

232 *reinholdii* (Kanaya and Koizumi, 1970) Zielinski and Gersonde, 2002 (which Macharè and

233 Fourtanier referred to as *Nitzschia reinholdii*) and *Shionodiscus oestrupii* (Ostenfeld, 1900)

234 Alverson, Kang and Theriot, 2006 (which Macharè and Fourtanier referred to as *Thalassiosira*

235 *oestrupii*). Although this attribution may still be valid, it is based on the assumption that *K.*

236 *tatsunokuchiensis* and *S. oestrupii* first appear in the Pliocene, as reported by Barron (1985). More

237 recently, the range of *K. tatsunokuchiensis* has been extended back in time and the species is now

238 known to span from 9.0 Ma to 2.6 Ma (Barron 2003, middle-to-high-latitude planktonic diatoms in

239 the North Pacific, B03's M-HLNP hereafter), while the FO of *S. oestrupii* is calibrated in the late

240 Miocene at 5.6 Ma (Barron 2003; tropical planktonic diatoms in the Equatorial Pacific, B03's EP

241 hereafter).

242 Diatoms were also used by Schrader and Ronning (1988) to date some stratigraphic sections

243 of the Pisco Fm. Although they refer to Barron's 1985 Equatorial Pacific zonation, Schrader and

244 Ronning (1988) used the species ranges of Barron both in the Equatorial Pacific zonation and in his

245 high latitude north Pacific zonation (Barron, 1985). Schrader and Ronning (1988) and Macharè and

246 Fourtanier (1987) used *Coscinodiscus plicatus* to date the Pisco Fm., ascribing to this species a LO

247 older than ca. 8 Ma. We draw attention to the work of Tanimura (1996), who taxonomically re-

248 examined specimens of plicated *Thalassiosira* from DSDP North Pacific Site 173, thus implying a

249 revision of the attribution of specimens of the Pisco Fm. to *C. plicatus*.

250 Tsuchi et al. (1988) also used diatoms to date outcrops of the Pisco Fm. exposed in the Ica

251 River Valley; they recognised different diatom zones of Barron's 1985 low-latitude diatom zonation

252 and referred these outcrops to the Miocene. Conversely, they attributed a late middle-late upper

253 Miocene through Pleistocene ages for diatomaceous outcrops in the Sacaco area (see Tsuchi et al.

254 1988 for outcrop locations).

255 Both middle-to-high-latitude North Pacific and low-latitude (Equatorial) Pacific zonations

256 (Barron 1985) have been used in recent works by Di Celma et al. (2016a, 2016b). In particular,

257 because of the co-occurrence of *Denticulopsis praekatayamae* Yanagisawa and Akiba, 1990 *(D.*

258 *hustedtii* in Di Celma et al. 2016a) and *Lithodesmium reynholdsii* Barron, 1976, the sedimentary

259 succession exposed at CC was referred to the subzone D of the *Denticulopsis hustedtii -*

260 *Denticulopsis lauta* zone of the middle-to-high-latitude North Pacific zonation (Di Celma et al.

261 2016a). On the other hand, species ranges from the low-latitude Pacific zonation were used to date

262 the CLQ site; the stratigraphy spanning from 213.4 m to 277.4 m abs was constrained to the base of

263 the *Fragilariopsis miocenica* zone (the low-latitude Pacific zonation, Barron 1985) thanks to the co-

264 occurrence of *Nitzschia porteri* Frenguelli, 1949 *sensu* Burckle, 1972 and *Fragilariopsis miocenica*

265 (Burckle, 1972) Censarek and Gersonde, 2002 (Di Celma et al., 2016b).

266 In this work we will present and discuss in detail biostratigraphic and geochronological data

267 reported by Di Celma et al. (2016a, 2016b). In contrast to Di Celma et al. (2016a), where data from

268 CC were referred to the middle-to-high-latitude North Pacific zonation of Barron (1985), in this

269 study data obtained from both CC and CLQ were referred to the Pacific low Latitude zonation of

270 Barron (1985) to make the results more uniform.

271

272 **3. Materials and Methods**

273

3.1. Biostratigraphic methods

Samples for biostratigraphic analysis were collected at about 4-5 m vertical spacing along the sections measured at CC and CLQ (enumeration of diatomite samples along the CLQ section is not sequential because samples were collected during different field seasons and along different sections that were subsequently merged together). Selected samples were dried and 0.2 g of each were treated in beakers with H_2O_2 and HCl to remove organic matter and carbonates. The residue was repeatedly diluted in demineralised water until the pH reached a value of ca. 5. To prepare the slides, 600 µL of solution were pipetted on a cover slip previously wet with distilled water. Once dried, cover slips were mounted on microscope slides using a small amount of Norland Optical Adhesive 61 (NOA 61[©]). Observations were made by means of a Leitz Diaplan [™] light microscope at 630x and 1000x.

The presence and relative abundance of different diatom species were tabulated (Tables 2 and 3). The total abundance of diatoms relative to the remaining sediment (glass shards and other minerals) was assessed according to Koç and Scherer (1996):

D = dominant; >60% valves.

A = abundant; ~20%–60% valves.

C = common; ~5%–20% valves.

F = few; 2%–5% valves.

R = rare; <2% valves.

B = barren; no diatoms present.

The relative abundance of each diatom taxon was estimated using the following qualitative scale:

A = abundant; >10 valves/fields of vision (FOV).

C = common; 1–10 valves/FOV.

297   F = few; ≥1 valve/10 FOVs and <1 valve/FOV.

298   R = rare; ≥3 valves/traverse of coverslip and <1 valve/10 FOVs.

299   X= present; <3 valves/traverse of coverslip, including fragments.

300   B = barren; no valves.

301 Diatom preservation categories, as reported in range charts, are described qualitatively according to

302 Barron and Gladenkov (in Rea et al. 1993):

303   VG = very good (no breakage or dissolution).

304   G = good (majority of specimens complete, with minor dissolution and/or breakage and no

305   significant enlargement of the areolae or a dissolution of frustule rims detected).

306   M = moderate (minor, but common areolae enlargement and dissolution of frustule rims,

307   with a considerable amount of breakage of specimens).

308   P = poor (strong dissolution or breakage, some specimens unidentifiable, strong dissolution

309   of frustule rims and areolae enlargement).

310 The diatom zonal scheme used here mainly follows biostratigraphic studies by Barron (1985). First

311 and Last Occurrences (FO and LO) of species are after the works of Barron (1985, 2003).

312 Therefore, all diatom bioevents are discussed referring to the Geochronologic and

313 Chronostratigraphic Time Scale of Berggren et al., 1995 (the one followed by Barron 2003); the

314 terms lower, middle, upper (chronostratigraphy) and early, middle, late (geochronology) referred to

315 subepochs are used as in Berggren et al., 1995 as well.

316 In this work, we refer to diatom species taking into account the most up-to-date taxonomic

317 revisions. This may create some confusion when comparing our data to older papers. In particular,

318 many specimens, previously determined as *Coscinodiscus plicatus* in numerous biostratigraphic

319 papers, have been moved into one of the many plicated *Thalassosira* species. We refer to

320 Tanimura's revision (1996) to identify the plicated *Thalassiosira* specimens that we encountered in

321 our sections, and to Yanagisawa and Akiba (1990) for the taxonomy of the species belonging to the

322 genus *Denticulopsis*.

323 Also, we provide ages of FO and LO in Ma; those are proceeded by the abbreviation 'ca.'

324 when referring to an uncalibrated age (i.e., when ages are only provided as ranges in illustrations of

325 biostratigraphic schemes).

326

327 *3.2. Volcanic ashes*

328 The volcanic ash layers were described in the field for thickness, lateral continuity, grading, colour,

329 presence of crystals (in particular biotite, which can be easily recognised with a hand-lens and

330 which is of interest for age determinations). The ash samples were examined under a

331 stereomicroscope and, where necessary, with smear slides analyses, with particular attention to

332 those showing biotite or sampled in a stratigraphic position suitable for correlating different

333 sections. Grain-size distribution was determined with a Malvern Mastersizer 2000E™ Laser

334 Granulometer at the University of Milano Bicocca. Crystals (sanidine and biotite) and glass shards

335 were prepared in polished resin mounts and carbon-coated for scanning electron microscopy in

336 backscattered electron imaging (SEM-BSE imaging) and for microanalytical investigations. Energy

337 dispersive X-ray spectroscopy analysis (SEM-EDS) analysis was carried out with a Philips™ XL30

338 scanning electron microscope equipped with Dx4i microanalysis at Dipartimento di Scienze della

339 Terra of the University of Pisa, with 20 kV filament voltage, 5 nA beam current and ZAF

340 correction. Electron probe microanalysis (EPMA) was carried out with a JEOL JXA-8600™ at

341 Consiglio Nazionale delle Ricerche, Florence and with a JEOL 8200 Superprobe™ at the University

342 of Milan. Analytical conditions were 15kV accelerating voltage, 5nA beam current, 3 μm beam

343 focus for biotite and 10 μm for feldspars.

344   Five samples were selected for biotite and sanidine picking, among those representative of

345   ash layers showing only evidence of primary transport mechanisms (airfall, ocean currents,

346   downward gravity currents; see Griggs et al. 2014).

347

348   *3.3. $^{40}Ar/^{39}Ar$ geochronology*

349

350   The samples selected for $^{40}Ar/^{39}Ar$ dating were wet-sieved through 500-250-125-63 µm mesh

351   sieves. Biotite and feldspar crystals in the 125-500 µm size range were hand-picked carefully

352   avoiding crystals with evident signs of alteration. For feldspars, a fraction of the picked crystals was

353   mounted on a glass slide to check identification with SEM-EDS.

354   Picked biotites and feldspars of each sample were wrapped in aluminium and irradiated in the

355   McMaster University nuclear reactor (Ontario, Canada) for 50 hours. The age monitor was

356   hornblende MMhb1 with an assumed age of 523.1 Ma (Renne et al. 1998). The vertical gradient

357   was ca. 1 %/cm.

358    $^{40}Ar/^{39}Ar$ analyses by step-heating following the procedures described by Villa et al. (2000) were

359   performed on the NuInstruments™ Noblesse® noble gas mass spectrometer at the University of

360   Milano-Bicocca equipped with one Faraday cup with a 10^{11} Ohm resistor and two ion counters.

361   The analytical protocol consisted of four measurement cycles to allow an in-run cross-calibration of

362   the relative collector gains, F/IC0 and IC0/IC1: ^{40}Ar (F), ^{38}Ar (IC0), ^{36}Ar (IC1); ^{39}Ar (F), ^{37}Ar

363   (IC0), ^{35}Cl (IC1); $^{41}C_3H_5$ (F), ^{39}Ar (IC0), ^{37}Ar (IC1); ^{38}Ar (F), ^{36}Ar (IC0). Each measurement

364   consisted of 40 repetitions of the four cycles, so as to avoid artefacts due to ion counter

365   nonlinearities (Barberini and Villa 2015).

366

367   **4. Results**

368

369   ***4.1. Biostratigraphy: distribution of marker species along the CC and CLQ sections***

370

371   *4.1.1. CC Lower and Upper Allomember sections*

372

373   Both the Lower and the Upper Allomember of CC were deposited in high-energy nearshore and

374   shelf settings. Sandstones are common and are characterised by neritic benthic diatom genera, such

375   as *Diplomenora and Odontella* and also by rare freshwater genera, such as *Stauroneis*; species

376   belonging to these genera are commonly long-ranging species and are not useful for biostratigraphy.

377   Diatomites are rare, especially in the lower portions of both allomembers, and only few samples are

378   useful for biostratigraphic purposes.

379   In the Lower Allomember (0-75.0 m abs), stratigraphically useful species are *Koizumia*

380   *tatsunokuchiensis* (sample CCD35, 35.7 m abs, FO = 9.0, LO = 2.6 Ma, ages of B03's M-HLNP;

381   Table 2, Fig. 3A, B), *Denticulopsis praekatayamae* (present from sample, CCD3, 1.0 m abs, to

382   sample CCD64, 62.5 m abs; FO = 9.5 Ma, LO = 8.5 Ma, B03's M-HLNP; Table 2, Fig. 3C, D) and

383   *Lithodesmium reynoldsii* (from sample CCD16, 11.5 m abs, to sample CCD52, 51.5 m abs; FO =

384   9.9 Ma, LO = 8.9 Ma, ages for the B03's M-HLNP; Table 2, Fig. 3E, F, G). Apparently, *L.*

385   *reynoldsii* is only present in the CC Lower Allomember, while probably reworked *D.*

386   *praekatayamae* appears sporadically also in the sediments of CLQ (but not in the Cerro Colorado

387   Upper Allomember. See Tables 2 and 3).

388   At 153.3 m (sample CCD92, Upper Allomember) rare specimens of *Thalassiosira antiqua*

389   (Grunow, 1884) Cleve-Euler, 1884 (FO = 8.5, LO = 1.6 Ma, ages of B03's M-HLNP) are present

390   (Table 2, Fig. 3H).

391

392   *4.2.2.CLQ section*

393

Similarly to CC, biostratigraphically useful species are rare along the CLQ measured section. Although diatomites are common, genera typical of upwelling environments, such as *Chaetoceros*, *Coscinodiscus* and *Thalassionema* dominate the assemblages. Nonetheless, specimens of marker species are present and help to constrain the age of the section.

Specimens of *Thalassiosira antiqua* are present from 72.9 to 96.5 m abs (from sample CLQ15-D19 to sample CLQD53; Table 3, Fig. 3I, J). Some of these specimens are smaller than those of *T. antiqua* at CC and their central rosette are more regular than those of the CC specimens (Gariboldi, 2016).

Fragilariopsis reinholdii (FO 7.6 Ma, LO 0.62 Ma ages of tropical planktonic diatoms in the B03's EP) is observed from 61.2 m abs throughout the section up to 286.8 m abs (from sample CLQ15-D16 to sample CLQD17; Table 3, Fig. 3K). Also *Koizumia tatsunokuchiensis* (FO 9.0 Ma LO 2.6 Ma, ages for the B03's M-HLNP) is pervasive in the section (from 113.1 m to 236.8 m abs, from sample CLQD57 to sample CLQD52; Table 3, Fig. 3A, B). *Nitzschia porteri* (FO 12.2 Ma, LO 7.1 Ma ages of B03's EP, Fig. 3L, M) is observed starting from 27.8 m abs (sample CLQD15-10, Table 3) up to 277.4 m abs (CLQD14, Table 3), its distribution crossing the intraformational unconformity (updated data if compared to those published in Di Celma et al., 2016b); in addition, *Fragilariopsis miocenica* (FO 7.3 Ma, LO 6.1 Ma ages of B03's EP; Fig. 3N) is observed from 213.4 m (CLQD42) up to 277.4 m abs (CLQD14), therefore co-occurring with *N. porteri* from 213.4 m abs to 277.4 m abs (Table 3).

Plicated *Thalassiosira* specimens (Fig. 3O) are present from 27.8 m abs (CLQ15-D10) up to 289.5 m abs (CLQD19), their distribution crossing the intraformational unconformity (Table 3). SEM imagery have revealed morphological affinities of some of these specimens with *Thalassiosira flexuosa* (Brun, 1894) Akiba and Yanagisawa, 1986 as described by Tanimura (1996); those have been identified as *Thalassiosira* cf. *flexuosa* (Gariboldi, 2016).

4.3. Volcanic ash layers

420

Over eighty volcanic ash layers were identified in the field along the CC (23 ash layers) and CLQ (59 ash layers) measured sections (Di Celma et al. 2016a, 2016b). Several other ash layers occur in the same successions, but too thin and discontinuous, or too similar in colour and grain-size to the marine sediments, to be distinguished.

The ash layers are mostly unconsolidated tephra; in some cases they are tuffs cemented by secondary minerals. Their base is usually sharp and marked by coarser grain-size and concentrations of crystals, when present, while the top may be sharp, irregular or diffuse, indicating variable influence of post-depositional reworking factors (currents, bioturbation). At the base, a hard gypsum/anhydrite crust of a few millimetres is commonly found. Tephra thickness is mostly 5-15 cm, but some thicker tephra (up to 50 cm), organised in different sublayers, have been found. The colour is largely grey to light grey, with transparent glass; grey to dark grey tephra are less frequent. Grain-size corresponds to unimodal or bimodal fine, very fine or extremely fine ashes, mainly moderately to well sorted (White and Houghton 2006). In the majority of tephra the components are dominated by glass shards (>85-95%), with variable amounts of juvenile crystals (biotite, sanidine and plagioclase) and traces of terrigenous and biogenic materials (Fig. 4A), but some ash layers contain >15% of non-primary material, such as rock fragments, heterogeneous crystals assemblages with olivine, pyroxene, quartz, diatoms, un-identified reddish aggregates. These were interpreted as tephra modified by reworking.

Among the primary ash layers, three samples for CLQ and two for CC were selected for biotite and sanidine hand-picking for $^{40}Ar/^{39}Ar$ dating. Some physical and chemical characteristics of the primary ash layers selected for age determinations or most useful for correlations are reported in Table S1 (supplementary material).

The composition of tephra selected for dating is rhyolitic. BSE imaging of samples selected for $^{40}Ar/^{39}Ar$ dating does not reveal alteration by secondary mineral development (Fig. 4B, C), although minor alteration could not be excluded. Mineral chemistry data of biotite, sanidine and plagioclase

446   is reported in Table S2 (supplementary material) and shown in Fig. 5 A, B and C (supplementary

447   material).

448   Mineral chemistry data provide evidence that different sanidine-plagioclase pairs of clusters

449   identify different samples (Fig. 5 A), suggesting that mineral chemistry could be used to fingerprint

450   tephra in relevant stratigraphic positions. The same occurs for biotite chemical composition: the

451   crystals of different samples plot in clusters which are non-overlapping for several chemical

452   parameters (e.g. $Mg/(Mg+Fe^{2+}_{tot}+Mn)$ vs. Ti), while they are rather homogeneous considering the

453   core-to-rim variations (Fig. 5 B, C). Some samples show a few outliers, which can be interpreted as

454   foreign biotite crystals entrained during the eruption or deposition. Of those analysed, only the

455   biotite crystals of sample CLQ-T9b form two distinct clusters (Fig. 5B, C).

456

457   *4.4. $^{40}Ar/^{39}Ar$ geochronology: results*

458

459   Four ash layers out of the selected five were suitable for dating. We analysed one ash layer from

460   CC, CC-T1b, located 30.5 m abs from CC (Fig. 2A) and three ash layers from the succession of

461   CLQ: CLQ-T49 (127.5 m abs, located on top of the Ballena marker bed, Fig. 2B); CLQ-T1a (the

462   Mono marker bed, 238.5 m abs, Fig. 2B); CLQ-T9b, the highest ash layer of the succession (289.5

463   m abs, Fig. 2B).

464       $^{40}Ar/^{39}Ar$ analyses were carried out on both biotite and feldspar separates. Table S3

465   (supplementary material) reports the analytical data for each sample. Age spectra were either

466   concordant (when several consecutive steps have the same "plateau" age, usually taken as the

467   accurate age of the sample) or discordant (when step ages give no plateau, in which case the

468   sample's age can be difficult to estimate). All of the present feldspar separates yielded discordant

469   age spectra; their unreliable ages suggest that they were contaminated by xenocrystic or detrital

470   grains, as also suggested by Smith at al. (2006), and/or by alteration phases, as required by the

471   excessively high Cl/K ratios.

472   In Figs. 6A and 6B, we show the age spectra obtained from ^{40}Ar/^{39}Ar analyses on biotite

473   separates. Sample CC-T1b (Fig. 2A) gave a plateau age of 9.10 ± 0.04 Ma (2σ error). In the CLQ

474   succession, samples CLQ-T49 and CLQ-T1a gave ages of 7.55 ± 0.05 Ma and 6.93 ± 0.09 Ma,

475   respectively (Fig. 6B). In these cases, ages were calculated only from the heating steps whose

476   chemical signature (both Ca/K and Cl/K ratios) was both uniform and typical of genuine biotite;

477   steps with anomalously high Ca/K and Cl/K ratios were attributed to contamination and/or

478   alteration phases, and not considered (Fig. S2, supplementary material). For sample CLQ-T9b a

479   discordant age spectrum was obtained, with step ages increasing steadily from 3.2 ± 0.7 Ma to 6.71

480   ± 0.02 Ma (Fig. 6B). Figs. 6C, D show that the biotite separate of CLQ-T9b contains two different

481   biotite populations. Fig. 6C shows a linear trend, evidence of a mainly binary mixing between one

482   Ar reservoir having a high Cl/K ratio (and also, as seen in supplementary Fig. S2 J, a low Ca/K

483   ratio) and an age ≥ 6.71 Ma, and one Ar reservoir having an age ≤ 3 Ma, low Cl/K and high Ca/K.

484   We interpret the former Ar reservoir as the magmatic biotite and assign an age of ≥ 6.71 ± 0.02 Ma.

485   The bimodal distribution of phases in the analysed separate is confirmed by Fig. 6D where we can

486   identify a cluster with a higher $Mg/(Mg+Fe^{2+}_{tot}+Mn)$ and lower alkalies; the substoichiometric

487   Na+K+Ca interlayer occupancy is evidence that this population consists of non-primary, altered

488   biotite that gives inaccurately low apparent ages.

489

490   **5. Discussion**

491

492   The absolute ages of many LO and FO of diatom markers that we observed are well known in the

493   Pacific. However, specimens of stratigraphically useful pelagic species are rare in the sediments of

494   both CC and CLQ, mainly due to dilution by abundant neritic and/or upwelling-characteristic

495   species. Moreover, the timing of marker species ingression in the basin may have been related to the

496 flow of oceanic currents into it. As a consequence of these two phenomena, bioevents can appear

497 delayed (FO) or anticipated (LO) in the basin if compared to pelagic settings.

498 Integration with $^{40}Ar/^{39}Ar$ data validates our biostratigraphic results. These, as well as

499 $^{40}Ar/^{39}Ar$ ages, place both successions of CC and CLQ in the late Miocene.

500 The oldest $^{40}Ar/^{39}Ar$ age was obtained for the base of the CC succession (9.10 ± 0.04 Ma for

501 the Lower Allomember, 30 m abs) and younger ages for the succession at CLQ (from the lowest to

502 the highest: 7.55 ± 0.05 Ma; 6.93 ± 0.09 Ma; t ≥ 6.71 ± 0.02 Ma).

503

504 *5.1. Diatom biostratigraphy and chronostratigraphy of the CC Lower Allomember.*

505

506 At CC, the Pisco Fm. lies directly on the Chilcatay Fm. and the base of our CC section is

507 also the base of the Pisco Fm. However, the base of the Pisco Fm. is diachronous throughout the

508 Basin and could be older or younger at other sites. The co-occurrence of *L. reynoldsii* (FO = 9.9

509 Ma, LO = 8.9 Ma, Barron 2003, Fig. 3E, F, G) and of *D. praekatayamae* (FO = 9.5, LO = 8.5 Ma,

510 Barron 2003, Fig. 3C, D) from 11.5 m to 51.5 m abs (samples CCD16 to CCD52, Table 2)

511 constrains the age of this part of the section between 9.5 and 8.9 Ma (Barron 2003), corresponding

512 to the *Thalassiosira yabei* zone (Fig. 7) of the Pacific low Latitude zonation of Barron (1985). Our

513 results differ from previous younger and older age assignments for *L. reynoldsii* (respectively ca.

514 6.5-5.7 Ma, Fig. 9.1 of Schrader and Ronning 1988 and ca. 10-11 Ma, Macharè and Fourtanier

515 1987) but agree with the 9.10 ± 0.04 Ma $^{40}Ar/^{39}Ar$ age that we obtained at 30.6 m abs (CC-T1) (Fig.

516 2A). Our combined data thus confirm a late Miocene (Tortonian) age for CC Lower Allomember

517 and amend previous age assignment to the middle Miocene (Bianucci et al. 2010; Lambert et al.

518 2010a, b; Parham and Pyenson, 2010; Pimiento and Balk, 2015) based on the occurrence of

519 *Anadara sechurana*, a bivalve that was typically found in the middle Miocene of the Pisco Basin

520 (DeVries 1998). As such, our results extend the range of *A. sechurana* into the upper Miocene of

521 the Pisco Basin, as also found in Panama (Austin Hendy personal communication).

5.2. Diatom biostratigraphy and chronostratigraphy of the CC Upper Allomember and of CLQ

Important biostratigraphic markers do not occur in the CC Upper Allomember, apart from *Thalassiosira antiqua*, which is present at 153.3 m abs (CCD92, Table 2, Fig. 3H).

Specimens of *T. antiqua* are also present at CLQ from 72.9 m to 96.5 m abs (from sample CLQ15-D19 to sample CLQD53 Table 3, Fig. 3I, J). This observation, coupled with the finding of the same internal unconformity at CC and CLQ, leads us to state that the CC Upper Allomember correlates with the portion of CLQ section above 29 m abs. The range of *T. antiqua* is calibrated to the middle to high-latitude North Pacific and its range spans from 8.5 Ma to 1.6 Ma (Barron 2003), suggesting that sediments of CC above sample CCD92 (153.3 m abs) and sediments of CLQ above sample CLQ15-D19 (72.9 m abs) are younger than 8.5 Ma. Although First and Last Occurrences of the cold-water *T. antiqua* should be considered with caution as bioevents along the CLQ section, the 7.55 ± 0.05 Ma radiometric age obtained for the CLQ-T49 tephra (127.5 m abs) is in agreement with a calibrated age of 8.5 Ma for the FO of *T. antiqua*. Notwithstanding the absence of dated tephra in the CC Upper Allomember, the occurrence of *T. antiqua* at 153.3 m abs and the consequent correlation with the CLQ 72.9-96.5 m abs interval (Table 2 and 3) allow us to infer that the age-range of the CC Upper Allomember is very close to a range between 8.5 Ma and 7.55 ± 0.05 Ma.

At CLQ, in the stratigraphic interval spanning from 213.4 to 277.4 m abs (Table 3, updated data compared to those published in Di Celma et al., 2016a), the co-occurrence of *Nitzschia porteri* (Fig. 3L, M) and *Fragilariopsis miocenica* (Fig. 3N) constrains the age between 7.3 Ma (FO of *F. miocenica*) and 7.1 Ma (LO of *N. porteri*), corresponding to the *Fragilariopsis miocenica* zone (Fig. 7) of the Pacific low Latitude zonation (Barron 1985; Table 3). *Fragilariopsis miocenica* was previously reported in the Pisco Fm. by Macharé and Fourtanier (1987) and Koizumi (1992) as *Nitzschia miocenica*. On the contrary, *N. porteri* was only reported by Koizumi (1992). If the 7.55 ±

0.05 Ma radiometric age at 127.5 m abs (CLQ-T49) agrees perfectly with the supposed FO of *F. miocenica* at 213.4 m abs (7.3 Ma), it could initially appear that the 6.93 ± 0.09 Ma radiometric age of CLQ-T1a, (238.5 m abs) disagrees with the LO of *N. porteri* (7.1 Ma), which is found 38.9 m above the CLQ-T1 tephra. This inconsistency is probably related to the need for a recalibration of the diatom bioevents in this oceanographic zone, and is certainly related to the fact that the systematic uncertainty of the bioevent ages is heavily underestimated (under no circumstances can a calibration from an interpolation derived from measurements be zero). If one takes into account a conservative estimate of ± 0.1 Ma propagated uncertainty for any bioevent, it becomes evident that the disagreement disappears. The disappearance of *T. antiqua* in the CLQ sediments well before the 7.3 - 7.1 Ma interval (Table 3) confirms that the range of the species in the Pisco Fm. does not reflect its full range observed in the high-latitude North Pacific.

We therefore confirm that the sedimentary succession exposed at Cerro Los Quesos is late Miocene in age, as stated by Di Celma et al. (2016a) and in contrast to what suggested by previous authors who placed Cerro Los Quesos in the middle Miocene (Lambert et al. 2009).[40]Ar/[39]Ar ages obtained for CLQ agree with those provided by Esperante et al. (2015) for the same site, spanning from 7.73 to 7.11 Ma, although the latter are provided without stratigraphic positioning.

5.3. Comments on other diatom biostratigraphic markers.

Some other species used as stratigraphic markers in the Pacific zonations are present in the Pisco Fm. Because their presence may be useful for a future zonation of the Pisco Fm., we list them here briefly. For a detailed discussion see Gariboldi (2016).

Koizumia tatsunokuchiensis (Fig. 3A, B) is present at CC at 35.7 m abs (sample CCD35, Table 2) and at CLQ in the 113.1 – 236.8 m abs interval (samples CLQD57-CLQD52, Table 3). Its range is used in the middle-to-high-latitude North Pacific zonation (Barron 1985) and has recently

been amended: it spans from 9.0 Ma to 2.6 Ma (species ranges of B03's M-HLNP). Our work

further supports that *K. tatsunokuchinesis* has a long range that begins in the Tortonian.

We also report the presence of plicated *Thalassiosira* specimens (Fig. 3O) in four CC

samples, both in the Lower and Upper Allomember (CCD5, 1.8 m abs; CCD42, 43.2m abs; CCD58,

57.7 m abs; CCD86, 131.7 m abs, Table 2) and throughout the CLQ section (CLQ15-D10, 27.8 m

abs - CLQD19, 289.5 m abs, Table 2). Plicated *Thalassiosira* specimens of the Pisco Fm. were

identified as *Coscinodiscus plicatus* by Schrader and Ronning (1988) and by Macharé and

Fourtanier (1987). Schrader and Ronning (1988) assigned to them a range from ca. 9 Ma to ca. 8

Ma (fig. 9-1 Schrader and Ronning 1988), while Macharè and Fourtanier (1987) used the range

proposed in Barron's zonation (1985) (from ca. 14.1 to ca. 8.6 Ma). Following the revision of

plicated *Thalassiosira* species made by Tanimura (1996), we identified some of the plicated valves

in the CLQ sediments as *Thalassiosira* cf. *flexuosa*, (Gariboldi, 2016), implying that age

attributions operated by Macharè and Fourtanier (1987) and Schrader and Ronning (1988) using the

C. plicatus ranges should be revised (Gariboldi, 2016).

Finally, we also point out that the presence of *Delphineis urbinai* Gariboldi 2016 (Fig. 3P),

although not considered a marker species (Gariboldi, 2016), is restricted to 231.2 m abs of the CLQ

section (CLQD46; only one specimen was observed in sample CLQD11, 262.0 m abs Table 3).

5.4. CLQ Age models and relative sedimentation rates.

Given the few control points at CC, it was not possible to build an unambiguous age model for this

site. We built two alternative age models for CLQ, from Member C upwards. As discussed above,

bioevents in the Pisco Fm. are not to be considered as strictly constrained in time. However, to build

our first age model, we considered the first and last samples where *Fragilariopsis miocenica* and

Nitzschia porteri have been documented in the CLQ section, as if they were respectively their real

598   FO and LO (Fig.8A), plus the ^{40}Ar/^{39}Ar ages; a second age model was built taking into account only

599   ^{40}Ar/^{39}Ar ages (see Fig. 8B). For both models, we considered the CLQ-T9b tephra ($\geq$ 6.71 ± 0.02

600   Ma) as equal to 6.71 ± 0.02 Ma.

601   The first model is based on the two bioevents, the FO of *F. miocenica* at x = 7.3 ± 0.1 Ma and y =

602   213.5 ± 1 m abs, and the LO of *N. porteri* at x = 7.1 ± 0.1 Ma and y = 277.4 ± 1 m abs. The

603   resulting sedimentation rate is 32 cm/ka (Fig. 8A, black solid line); propagating uncertainties lead to

604   an extremely wide confidence interval,between 16 cm/ka (Fig. 8A, purple dotted line) and infinity

605   (Fig. 8A, blue dotted line), as the two LO/FO age estimates are so close to each other. It can be seen

606   that the extrapolation of the 32 cm/ka sedimentation rate downsection to the location of tephra

607   CLQ-T49 predicts an age of 7.57 Ma (Fig. 8A, black dotted line), in perfect agreement with its

608   ^{40}Ar/^{39}Ar age. In turn, hybridising the bioevent model with the one isotopic age of CLQ-T49 results

609   in a much lower uncertainty for the sedimentation rate, which becomes 33 ± 9 cm/ka (Fig. 8A,

610   orange dotted line). However, the other two ^{40}Ar/^{39}Ar ages of tephras CLQ-T9 and CLQ-T1a are

611   irreconcilable with both versions of this age model. Uncertanties related to sedimentation rates and

612   extrapolated ages were calculated by means of IsoPlot 2.06 (Ludwig 1999).

613   The second age model takes into account only the ^{40}Ar/^{39}Ar ages (Fig. 8B). The overall

614   sedimentation rate between CLQ-T9b and CLQ-T49 is 19 ± 1 cm/ka (Fig. 8B, black solid line); the

615   age of less precise intermediate biotite sample, CLQ-T1a, lies on the line defined by the two more

616   precise extreme samples, which would predict an age of 6.97 ± 0.03 Ma for it. This is compatible

617   with, but no firm proof of, a constant sedimentation rate. However, if this model is taken as

618   accurate, the FO of *Fragilariopsis miocenica* (7.3 ± 0.1 Ma) and the LO of *Nitzschia porteri* (7.1 ±

619   0.1 Ma) end up very far from the regression line, which assigns a calculated age of 7.1± 0.1 Ma and

620   of 6.7 ± 0.1 Ma to the FO and for the LO respectively for the elevation at which they are observed,

621   namely 213.5 ± 1 m abs and 277.4 ± 1 m abs. As the *N. porteri* specimens are not reworked, only

622   one explanation for this inconsistency in age model B appears tenable: the diatom bioevents that we

623   used were not calibrated in this oceanographic region.

624   On the whole, obtained sedimentation rates range from ca. 19 to ca. 33 cm/ka. As we

625   consider the extrapolation of open-ocean bioevent ages to the Pisco Basin problematic, we propose

626   that the most likely sedimentation rate is that shown in Age Model B based on ^{40}Ar/^{39}Ar ages (Fig.

627   8), 19 ± 1 cm/ka.

628   The obtained sedimentation rates are certainly very high but not exceptional if compared

629   with those of other high productivity basins, calculated on core sediments. We cite as examples: a)

630   Pleistocene of DSDP Site 478 (Gulf of California, DSDP Leg 64), >125 cm/ka (Schrader 1982); b)

631   Quaternary of ODP Site 686 (West Pisco Basin, ODP Leg 112), 16 cm/ka (Suess and Von Huene

632   1988); c) Pleistocene of ODP Site 1078 (outside the Bight of Angola, ODP Leg 175), 60 cm/ka

633   (Wefer et al. 1998); d) Pleistocene of ODP Site 881, 5.6 cm/ka and Mio-Pliocene of ODP Site 883,

634   9.1 cm/ka (Subarctic Pacific Ocean, ODP Leg 145; Rea et al., 1993) Because most of these

635   examples are all related to Quaternary sediments, we can hypothesise that such young sediments are

636   less compacted than those of the Miocene Pisco Fm. (and therefore not completely comparable).

637   We can correct for compaction using the approach of Isaacs et al. (1983), who proposed a

638   compaction of 60% for the Miocene diatomaceous sediments of the Monterey Fm., California. By

639   applying this percentage of compaction to the 19 cm/ka obtained in model B, a "real" sedimentation

640   rate of ca. 32 cm/ka (0.32 mm/a) would result. Therefore, although the proposed age models present

641   some issues, they demonstrate that the sedimentation rates that characterised the Pisco Fm. during

642   its deposition were not exceptional. These results strongly contrast with previous literature, which

643   suggested that the sedimentation rates in the Pisco Fm. were two to four orders of magnitude higher

644   (cm/a to m/a), to justify the exceptional preservation of fossils (Brand et al. 2004; Esperante et al.

645   2008, 2015).

646

647   **6. Conclusions**

648   This work combines detailed studies concerning the biostratigraphy and the geochronology in two

649   fossiliferous localities (CC and CLQ) of the Pisco Fm. that were recently investigated in detail from

a stratigraphic, geologic and palaeontologic point of view (Bianucci et al. 2016a, 2016b; Di Celma et al. 2016a, 2016b; Rustichelli et al. 2016a, b). These sites, previously referred to the middle Miocene, have now been re-assigned to the late Miocene, as strongly supported by the existing agreement between diatom biostratigraphy and $^{40}Ar/^{39}Ar$ dating. In particular:

- the CC Lower Allomember has been placed in the *Thalassiosira yabei* zone (late Miocene, Pacific low latitude zonation, Barron 1985) because of the co-occurrence of *Lithodesmium reynoldsii* (FO 9.9 Ma, LO 8.9 Ma) and *Denticulopsis praekatayamae* (FO 9.5 Ma, LO 8.5 Ma) and by means of $^{40}Ar/^{39}Ar$ dating (CC-T1 = 9.10 ± 0.04 Ma).
- Due to the presence of *Thalassiosira antiqua* the CC Upper Allomember is correlated with the section exposed above 29 m abs at CLQ.
- The portion of CLQ section from 213.4 m to 277.4 m abs has been referred to the late Miocene *Nitzschia miocenica* zone (Pacific low latutude zonation, Barron 1985) because of the co-occurrence of *Nitzschia porteri* and *Fragilariopsis miocenica* (7.3 Ma - 7.1 Ma).
- $^{40}Ar/^{39}Ar$ ages obtained from CLQ tephra indicate a late Miocene age for the >29 m abs section at this site, spanning from 7.55 ± 0.05 Ma (CLQ-T49) to t ≥ 6.71 ± 0.02 Ma (CLQ-T9b).

As a result, two very different age models for the site of CLQ are proposed here, which agree in estimating that the overall average sedimentation rate during the deposition of this section was ca. 19 cm/ka to at most ca. 33 cm/ka, in line with other high productivity basins.

As a consequence, it is possible to state that during its deposition the Pisco Fm. was characterised by sedimentation rates that are comparable to those of modern environments. This result leads to important conclusions:

a) although high sedimentation rates may have played a role, the exceptional preservation of fossils of the Pisco Fm. is likely to be due to some additional cause;

b) Contrary to statements in the literature, the sedimentation rates and environmental conditions during the accumulation of the sediments of the Pisco Fm. were similar to those of modern environments. As such, it is through the observation of the latter that a better understanding of the sedimentary and geochemical processes that led to the formation of the Pisco Lagerstätte can be reached.

The results stemming from this work do not only provide a high-resolution chronostratigraphic framework for the fossil vertebrate fauna occurring at CC and CLQ. They also represent a first step of a wider research in progress that endeavours to reconstruct, with the same approach, a complete framework of the Pisco Fm. and subsequently of the entire marine stratigraphic succession deposited in the Pisco Basin from the middle Eocene to the late Pliocene. This broad final result will be fundamental to reconstruct in detail the evolutionary patterns of the marine vertebrates of the Pisco Basin and to correlate them with those on a global scale.

Bibliography

700 - Akiba, F., 1985. Middle Miocene to Quaternary diatom biostratigraphy in the Nankai Trough and

701   Japan Trench, and modified Lower Miocene through Quaternary diatom zones for middle-to-

702   high latitudes of the North Pacific. DSDP Initial Reports, 87, p. 393-480.

703 - Akiba, F., Yanagisawa, Y., 1986. Taxonomy, morphology and phylogeny of the Neogene diatom

704   zonal marker species in the middle-to-high latitudes of the North Pacific. DSDP Initial Reports,

705   87, p. 483-554.

706 -Alverson, A.J., Kang, S.H. Theriot, E.C., 2006. Cell wall morphology and systematic importance

707   of *Thalassiosira ritscheri* (Hustedt) Hasle, with a description of *Shionodiscus* gen. nov. Diatom

708   Research 21(2), p. 215-262.

709 - Barazangi, M., Isacks, B. L., 1979. Subduction of the Nazca plate beneath Peru: evidence from

710   spatial distribution of earthquakes. Geophysical Journal International, 57(3), p. 537-555.

711 - Barberini, V., Villa., I., 2015. Ion Counter Nonlinearities. Goldschmidt2015 Abstracts: 202.

712 - Barron, J. A., 1983. Latest Oligocene through early middle Miocene diatom biostratigraphy of the

713   eastern tropical Pacific. Marine Micropaleontology, 7(6), p. 487-515.

714 - Barron, J.A., 1976. Revised Miocene and Pliocene diatom biostratigraphy of upper Newport Bay,

715   Newport Beach, California. Marine Micropaleontology, 1, p. 27-63.

716 - Barron, J.A., 1985 Miocene to Holocene planktic diatoms. In H. M. Bolli, J. B. Saunders, & K. P.

717   Perch-Nielsen (Eds.), Plankton stratigraphy (pp. 763–809). Cambridge: Cambridge Univ. Press.

718 - Barron, J.A., 2003. Planktonic marine diatom record of the past 18 my: appearances and

719   extinctions in the Pacific and Southern Oceans. Diatom Research, 18(2), p. 203-224.

720 - Berggren, W.A., Kent, D.V., Swisher, C.C., Aubry, M.P., 1995. A Revised Cenozoic

721   geochronology and chronostratigraphy. In: Berggren, W.A., Kent, D.V., Hardenbol, J. (Eds.),

722   Geochronology, Time Scales and Global Stratigraphic Correlation. Society of Economic

723   Paleontologists and Mineralogists, Special Publication, Tulsa, 54 p. 129-212.

724 - Bianucci, G., Lambert, O., Post, K., 2010. High concentration of long-snouted beaked whales

725   (genus *Messapicetus*) from the Miocene of Peru. Palaeontology, 53(5), p. 1077-1098.

726 - Bianucci, G., Di Celma, C., Landini, W., Post, K., Tinelli, C., Muizon, C. de, Bosio, G., Gariboldi,
727 K., Gioncada., A., Malinverno., E., Cantalamessa, G., Altamirano-Sierra, A., Salas-Gismondi.,
728 R., Urbina, M., Lambert, O., 2016a. Distribution of fossil marine vertebrates in Cerro Colorado,
729 the type locality of the giant raptorial sperm whale *Livyatan melvillei* (Miocene, Pisco Formation
730 Peru). Journal of Maps, 12(3), p. 543-557.

731 - Bianucci, C., Di Celma, C., Collareta, A., Landini, W., Post, K., Tinelli, C., Muizon, C. de,
732 Gariboldi, K., Malinverno., E., Cantalamessa, G., Gioncada, A., Collareta., A., Salas-Gismondi, R.,
733 Varas-Malca, R., Urbina, M., Lambert, O., 2016b. Fossil marine vertebrates of Cerro Los Quesos:
734 distribution of cetaceans, seals, crocodiles, seabirds, sharks, and bony fish in a late Miocene locality
735 of the Pisco Basin, Peru.. Journal of Maps 12(5), p. 1037-1046..

736 - Bianucci, G., Di Celma, C., Urbina, M., Lambert, O., 2016c. New beaked whales from the late
737 Miocene of Peru and evidence for convergent evolution in stem and crown Ziphiidae (Cetacea,
738 Odontoceti). PeerJ 4, p. e2479; DOI 10.7717/peerj.2479

739 - Brand, L., Esperante, R., Chadwick, A.V., Porras, O.P., Alomía, M., 2004. Fossil whale
740 preservation implies high diatom accumulation rate in the Miocene–Pliocene Pisco Formation of
741 Peru. Geology 32(2), p. 165–168.

742 - Brand, L., Urbina, M., Chadwick, A., DeVries, T.J., Esperante, R., 2011. A high resolution
743 stratigraphic framework for the remarkable fossil cetacean assemblage of the Miocene/Pliocene
744 Pisco Formation, Peru. Journal of South American Earth Sciences, 31, p. 414-425.

745 - Brun, J., 1894. Espèces nouvelles. Le Diatomiste, 2, p. 72-78.

746 - Burckle, L. H., 1972. Late Cenozoic planktonic diatom zones from the eastern equatorial Pacific.
747 Nova Hedwigia. Beihefte.

748 - Cahill, T., Isacks, B.L., 1992. Seismicity and shape of the subducted Nazca plate. Journal of
749 Geophysical Research: Solid Earth (1978–2012), 97(B12), p. 17503-17529.

750 - Censarek, B., Gersonde, R., 2002. Miocene diatom biostratigraphy at ODP Sites 689, 690, 1088,
751 1092 (Atlantic sector of Southern Ocean). Marine Micropaleontology, 45, p. 309-356.

752   - Collareta, A., Landini, W., Lambert, O., Post, K., Tinelli, C., Di Celma, C., Panetta, D., Tripodi,

753   M., Salvadori, P.A., Caramella, D., Marchi, D., Bianucci, G., 2015. Piscivory in a Miocene

754   Cetotheriidae of Peru: first record of fossilized stomach content for an extinct baleen-bearing

755   whale. The Science of Nature, 102(11-12), p. 1-12.

756   - DeVries, T.J., 1998. Oligocene deposition and Cenozoic sequence boundaries in the Pisco Basin

757   (Peru). Journal of South American Earth Sciences, 11, p. 217–231.

758   - Di Celma, C., Malinverno, E., Gariboldi, K., Gioncada, A., Rustichelli, A., Pierantoni, P. P.,

759   Landini, W., Bosio, G., Tinelli. C., Bianucci, G., 2016a. Stratigraphic framework of the late

760   Miocene to Pliocene Pisco formation at Cerro Colorado (Ica Desert, Peru). Journal of Maps,

761   12(3), p. 515-529.

762   - Di Celma, C., Malinverno, E., Cantalamessa, G., Gioncada, A., Bosio, G., Villa, I.M., Gariboldi,

763   K., Rustichelli, A., Pierantoni, P.P., Landini, W., Tinelli, C., Collareta, A., Bianucci, G., 2016b.

764   Geological Map of the Miocene-Pliocene Pisco Formation at Cerro Los Quesos (Ica Desert,

765   Peru). Journal of Maps, 12(5), p. 1020–1028.

766   - Dunbar, R.B., Marty, R.C., Baker, P.A., 1990. Cenozoic marine sedimentation in the Sechura and

767   Pisco Basins, Peru. Palaeogeography, Palaeoclimatology, Palaeoecology 77, p. 235-261.

768   - Ehret, D.J., MacFadden, B.J., Salas-Gismondi, R., 2009. Caught in the act: trophic interactions

769   between a 4-million-year-old white shark (Carcharodon) and mysticete whale from Peru. Palaios

770   24 (5), p. 329–333.

771   - Ehret, D. J., Macfadden, B. J., Jones, D. S., DeVries, T. J., Foster, D. A., Salas-Gismondi,R.,

772   2012. Origin of the white shark Carcharodon (Lamniformes: Lamnidae) based on recalibration of

773   the Upper Neogene Pisco Formation of Peru. Palaeontology, 55(6), p. 1139-1153.

774   - Esperante, R., Brand, L., Nick, K., Poma, O., Urbina, M., 2008. Exceptional occurrence of fossil

775   baleen in shallow marine sediments of the Neogene Pisco Formation, Southern Peru.

776   Palaeogeography, Palaeoclimatology, Palaeoecology 257, p. 344–360.

777 - Esperante, R., Brand, L.R., Chadwick, A.V., Poma, O., 2015. Taphonomy and paleoenvironmental

778   conditions of deposition of fossil whales in the diatomaceous sediments of the Miocene/Pliocene

779   Pisco Formation, southern Peru—a new Fossillagerstätte. Palaeogeography, Palaeoclimatology,

780   Palaeoecology, 417, p. 337–370.

781 - Frenguelli, J., 1949. Diatomeas fósiles de los yacimientos chilenos de Tiltil y Mejillones.

782   Darwinia, 9(1), p. 97-157.

783 - Gariboldi, K., 2016. A note on diatom stratigraphic markers in upper Miocene sediments of the

784   Pisco Formation, Peru, and description of *Delphineis urbinai* sp. nov. Diatom Research, 31(3), p.

785   285-301.

786 - Gariboldi, K., Gioncada, A., Bosio, G., Malinverno, E., Di Celma, C., Tinelli, C., Cantalamessa,

787   G., Landini, W., Urbina, M.. Bianucci, G., 2015. The dolomite nodules enclosing fossil marine

788   vertebrates in the East Pisco Basin, Peru: field and petrographic insights into the Lagerstätte

789   formation. Palaeogeography, Palaeoclimatology, Palaeoecology, 438, p. 81-95.

790 - Gioncada, A., Collareta, A., Gariboldi, K., Lambert, O., Di Celma, C., Bonaccorsi, E., Urbina, M.,

791 Bianucci, G., 2016. Inside baleen: Exceptional microstructure preservation in a late Miocene whale

792 skeleton from Peru. Geology, 44(10), p. 839-842.

793 - Griggs, A. J., Davies, S. M., Abbott, P. M., Rasmussen, T. L., Palmer, A. P., 2014. Optimising the

794   use of marine tephrochronology in the North Atlantic: a detailed investigation of the Faroe

795   Marine Ash Zones II, III and IV. Quaternary Science Reviews, 106, p. 122-139.

796 - Grunow, A., 1878. Algen und Diatomaceen aus dem Kaspischen Meere. W. Junk.

797 - Grunow, A., 1884. Diatomeen Von Franz Josef-Land. Denkschriften der mathematisch-

798   naturwissenschaftlichen Classe der Kaiserlichen Akademie der Wissenschaften, 48, p. 53-112.

799 - Grzybowsky, J. 1899. Die Tertiarablagerungdes nordlichen Peru und ihre Molluskenfauna. Neues

800   Jahrbuch Für Mineralogie, Geologie und Paläontologie, 12, p. 610-664.

801 - Gutscher, M.A., Maury, R., Eissen, J. P., Bourdon, E., 2000. Can slab melting be caused by flat

802   subduction?. Geology, 28(6), p. 535-538.

803   - Isaacs, C. M., Pisciotto, K. A., Garrison, R. E., 1983. Facies and diagenesis of the Miocene

804   Monterey Formation, California: a summary. Developments in Sedimentology, 36, p. 247-282.

805   - Kamimuri, S.I.; Motoyama, I., Nishi, I., Iwai, M., 2009. Neogene radiolarian biostratigraphy and

806   faunal evolution rates in the eastern equatorial Pacific ODP Sites 845 and 1241. Acta

807   Paleontologica Polonica, 54 (4), p. 713-742.

808   - Kanaya, T., Koizumi, I., 1970. The progress in the younger Cenozoic diatom biostratigraphy in the

809   northern circum-Pacific region. Journal of Marine Geology, 6, p. 47-66.

810   -Koç, N., Scherer, R.P., 1996. Neogene Diatom Biostratigraphy of the Iceland Sea Site 9071. In

811   Proceedings of the Ocean Drilling Program. Scientific Results, 151, p. 61-74.

812   - Koizumi, I., 1972. Marine diatom flora of the Pliocene Tatsunokuchi Formation in Fukushima

813   Prefecture. Transaction and Proceedings of the Paleontological Society of Japan, N.S., 86, p.

814   340-359.

815   - Koizumi, I., 1992. Diatomaceous sediments along the Pacific coastal areas of South America and

816   their evaluation. Journal of the Faculty of Science, Hokkaido University, Ser. IV, 23(2), p. 227-

817   245.

818   - Lambert, O., Bianucci, G., Muizon, C. de, 2008. A new stem-sperm whale (Cetacea, Odontoceti,

819   Physeteroidea) from the Latest Miocene of Peru. Comptes Rendus Palevol 7, p. 361–369.

820   - Lambert O., Bianucci G., Post K., 2009. A new beaked whale (Odontoceti, Ziphiidae) from the

821   middle Miocene of Peru. Journal of Vertebrate Paleontology, 29(3), p. 910-922.

822   - Lambert O., Bianucci G., & Post K., 2010a. Tusk-bearing beaked whales from the Miocene of

823   Peru: sexual dimorphism in fossil ziphiids?. Journal of Mammalogy, 91(1), p. 19-26.

824   - Lambert O., Bianucci G., Post K., Muizon C. de, Salas-Gismondi R., Urbina M., Reumer J.,

825   2010b. The giant bite of a new raptorial sperm whale from the Miocene epoch of Peru. Nature,

826   466(7302), p. 105-108.

827   - Lambert, O., Muizon, C. de, Bianucci, G., 2013. The most basal beaked whale *Ninoziphius*

828   *platyrostris* Muizon, 1983: clues on the evolutionary history of the family Ziphiidae (Cetacea:

829   Odontoceti). Zoological Journal of the Linnean Society 167, p. 569–598.

830   - Lambert, O., Bianucci, G., Beatty, B.L., 2014. Bony outgrowths on the jaws of an extinct sperm

831   whale support macroraptorial feeding in several stem physeteroids. Naturwissenschaften, 101,

832   517–521, DOI: 10.1007/s00114-014-1182-2

833   - Lambert, O., Collareta, A., Landini, W., Post, K., Ramassamy, B., Di Celma, C., Urbina, M.,

834   Bianucci, G., 2015. No deep diving: Evidence of predation on epipelagic fish for a stem beaked

835   whale from the late Miocene of Peru. In Proceedings of the Royal Society of London B,

836   282(1815): 20151530. The Royal Society.

837   - Lambert, O., Muizon, C. de, Bianucci, G., 2016. Macroraptorial sperm whales (Cetacea,

838   Odontoceti, Physeteroidea) from the Miocene of Peru. Zoological Journal of the Linnean

839   Society, doi:10.1111/zoj.12456.

840   - Lambert, O., Bianucci, G., Urbina M. , Geisler H.J., in press. A new inioid (Cetacea, Odontoceti,

841   Delphinida) from the Miocene of Peru and the origin of modern dolphin and porpoise families.

842   Zoological Journal of the Linnean Society.

843   -

844   - León, W., Aleman, A., Torres, V., Rosell, W., & De La Cruz, O., 2008. Estratigrafía,

845   Sedimentología y evolución tectónica de la cuenca Pisco Oriental. Boletín INGEMMET, 27

846   (Serie D), pp. 144, Lima, Peru.

847   - Ludwig, K.R., 1999. Isoplot/Ex 2.06, a geochronological toolkit for Microsoft Excel. Berkeley

848   Geochronology Center Special Publication 1a, 49 p.

849   - Macharé, J., Fourtanier, E., 1987. Datations des formations tertiaires du bassin de Pisco (Pérou) à

850   partir d'associations de diatomées. Comptes rendus de l'Académie des sciences. Série 2,

851   Mécanique, Physique, Chimie, Sciences de l'univers, Sciences de la Terre, 305(5), p. 407-412.

852   - Marty, R., 1989. Stratigraphy and chemical sedimentology of Cenozoic biogenic sediments from

853   the Pisco and Sechura Basins, Peru. PhD Thesis, Huston, Texas, Rice University.

854   - Maruyama, T., 1984. Miocene diatom biostratigraphy of onshore sequences on the Pacific side of

855   Northeast Japan, with reference to DSDP hole 438A (part 2). Science Reports of the Tohoku

856   University, Second Series, (Geology). 55, p. 77-140.

857   - Mertz D., 1966. Mikropaläontologische und sedimentologische Untersuchung der Pisco-

858   Formation Südperus. Palaeontographica Abteil B, 118, p. 1-51.

859   - Muizon, C. de, Bellon, H., 1980. L'âge mio-pliocène de la formation Pisco, Pèrou. Comptes

860   Rendus de l'Académie des Sciences de Paris, tome 290, Série D, p. 1063-1066.

861   - Muizon, C. de, Bellon, H., 1986. Nouvelles donn ees sur l'âge de la Formation Pisco (Pérou).

862   Comptes Rendus de l'Académie des Sciences de Paris, tome 303, Série II, no 15, p. 1401-1404.

863   - Muizon, C. de, DeVries, T.J., 1985. Geology and paleontology of alte Cenozoic marine deposits in

864   the Sacaco area (Peru). Geologische Rundschau, 74(3), p. 547-563.

865   - Olsson, A. A., 1932. Contributions to the Tertiary paleontology of northern Peru: part 5, the

866   Peruvian Miocene. Bulletins of American Paleontology, 19, p. 1-272.

867   - Ostenfeld, C.H., 1900. Plankton. In M. Knudsen and C.H. Ostenfeld, Iagttagelser over

868   Overfladevandets Temperatur, Saltholdighet og Plankton paa islandske og grønlandske

869   Skibsrouter I 1899. C.F. Wandel. Copenhagen.

870   - Parham, J. F., Pyenson, N. D., 2010. New sea turtle from the Miocene of Peru and the iterative

871   evolution of feeding ecomorphologies since the Cretaceous. Journal of Paleontology, 84(02), p.

872   231-247.

873   - Pilger, R. H., 1981. Plate reconstructions, aseismic ridges, and low-angle subduction beneath the

874   Andes. Geological Society of America Bulletin, 92(7), p. 448-456.

875   - Pimiento, C., Balk, M. A., 2015. Body-size trends of the extinct giant shark *Carcharocles*

876   *megalodon*: a deep-time perspective on marine apex predators. Paleobiology, 41(03), p. 479-490.

877   - Rea, D.K., Basov, I.A., Janecek, T.R., Palmer-Julson, A., et al., 1993 Proceedings of the Ocean

878   Drilling Program, Initial Reports, 145, p. 9-33.

879 - Renne, P. R., Swisher, C. C., Deino, A. L., Karner, D. B., Owens, T. L., DePaolo, D. J., 1998.

880   Intercalibration of standards, absolute ages and uncertainties in ^{40}Ar/^{39}Ar dating. Chemical

881   Geology,145(1), p. 117-152.

882 - Rustichelli, A., Di Celma, C., Tondi, E., Bianucci, G., 2016a. Deformation within the Pisco Basin

883   sedimentary record (southern Peru): stratabound orthogonal vein sets and their impact on fault

884   development. Journal of South American Earth Sciences, 65, p. 79-100.

885 - Rustichelli, A., Di Celma C., Tondi, E., Baud, P., Vinciguerra, S., 2016b. Fibrous gypsum veins as

886   diffuse features and within fault zones: the case study of the Pisco Basin (Ica desert, southern

887   Peru) Journal of the Geological Society, London, 173, doi:10.1144/jgs2015-084.

888 - Schrader, H., 1982. Diatom biostratigraphy and laminated diatomaceous sediments from the Gulf

889   of California Deep Sea Drilling Project Leg 64. In Curray, J. R., More, D. G., Kelts, K., &

890   Einsele, G., 1982. Proceedings of the Ocean Drilling Program, Part A: Initial Reports 64(2), p.

891   1089-1116.

892 - Schrader, H. and Ronning, P., 1988. Diatom biostratigraphy and coastal upwelling interpretation.

893   In: R. B.Dunbar and P. A. Baker (Editors), Cenozoic Geology of the Pisco Basin, IGCP no.156

894   Guidebook to Field Workshop, May 1988, Lima, p. 135-140.

895 - Simonsen, R., 1979. The diatom system: ideas on phylogeny. Bacillaria, 2, p. 9-71.

896 - Simonsen, R., Kanaya, T., 1961. Notes on the marine species of the diatom genus *Denticula* Kütz.

897   Internationale Revue der gesamten Hydrobiologie und Hydrographie, 46(4), p. 498-513.

898 - Smith, M. E., Singer, B. S., Carroll, A. R., Fournelle, J. H., 2006. High-resolution calibration of

899   Eocene strata: ^{40}Ar/^{39}Ar geochronology of biotite in the Green River Formation. Geology, 34(5),

900   p. 393-396.

901 - Suess, E., Von Huene, R., & ODP, L., 1988. 112 Scientific Party: Peru continental margin. In

902   Proc. ODP Init. Repts. 112, p. 5-23.

903 - Tanimura Y., 1996. Fossil marine plicated *Thalassiosira*: taxonomy and an idea on phylogeny.

904   Diatom Research, 11(1), p. 165-202.

905 - Tsuchi, R., Shuto, T., Takayama, T., Fujiyoshi, A, Koizumi, I., Ibaraki, M., Rangel, Z.C., Aldana,

906   A.M., 1988. Fundamental Data on Cenozoic Biostratigraphy of the Pacific Coast of Peru. In:

907   Report of Andean studies, Tsuchi R. (ed.), Shizuoka University. Special volume, 3, p. 45-70.

908 - Villa, I. M., Hermann, J., Müntener, O., Trommsdorff, V. 2000. $^{39}Ar - ^{40}Ar$ dating of multiply

909   zoned amphibole generations (Malenco, Italian Alps). Contributions to Mineralogy and

910   Petrology, 140(3), p. 363-381.

911 - Wefer, G., Berger, W. H., Richter, C., 1998. In Proc. ODP Init. Repts. 175. Texas A&M

912   University, College Station, Texas.

913 - White, J. D. L., Houghton, B. F., 2006. Primary volcaniclastic rocks. Geology, 34(8), p. 677-680.

914 - Yanagisawa, Y., 1994. *Koizumia* Yanagisawa gen. nov., a new marine fossil araphid diatom

915   genus. Transaction and Proceedings of the Paleontological Society of Japan. NS, 176, p. 591-

916   617.

917 - Yanagisawa, Y., Akiba, F., 1990. Taxonomy and phylogeny of the three marine diatom genera

918   *Crucidenticula*, *Denticulopsis* and *Neodenticula*. Bulletin of the Geological Survey of Japan, 41,

919   p. 197-301.

920 - Zielinski, U., Gersonde, R., 2002. Plio-Pleistocene diatom biostratigraphy from ODP Leg 177,

921   Atlantic sector of the Southern Ocean. Marine Micropaleontology, 45, p. 225-268.

922 - Zúniga-Rivero, F. J., Klein, G. D., Hay-Roe, H., Alvarez-Calderon, E. (2010). The hydrocarbon

923   potential of Peru. BPZ Exploración & Producción SRL, Lima, Peru.