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**New microfossil and strontium isotope chronology used to identify the controls of
Miocene reefs and related facies in NW Cyprus**

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Abbreviated Title - Miocene reefs and related facies in NW Cyprus

The existing chronostratigraphic framework in NW Cyprus of two-phase, Early and Late
Miocene reef and associated facies development is tested and improved using a combination
of calcareous nannofossil, benthic and planktic foraminiferal, and also Sr isotope dating.
Following localised Late Oligocene neritic carbonate deposition (e.g. benthic foraminiferal
shoals), reefs and related facies (Terra Member) began to develop c. 24 Ma (Aquitainian) and
terminated c. 16 Ma (end-Burdigalian). Early Miocene reef and marginal facies were then
extensively redeposited as multiple debris-flow deposits until c. 13.7 Ma, influenced by a
combination of global sea-level fall (related to growth of the East Antarctic Ice Sheet) and
local- to regional-scale tectonics. Reef growth and related deposition resumed (Koronia
Member) c. 9.1 Ma (Tortonian), then terminated by c. 6.1 Ma (mid-Messinian), followed by
the Messinian salinity crisis. Neritic accumulation in NW Cyprus began earlier (Late
Oligocene), than in southern Cyprus (Early Miocene). The Early Miocene reefs developed on

a c. N-S-trending structural high in the west (Akamas Peninsula area) whereas the Late Miocene reefs developed on both flanks of the neotectonic Polis graben. The two-phase reef development is mirrored in SE Cyprus and in some other Mediterranean areas; e.g. S Turkey, Israel, Italy, S Spain.

Key words: NW Cyprus, Miocene, Terra Member, Koronia Member, Polis graben, sea-level change, climate change.

Supplementary material: GPS Locations of dated samples, the Sr isotope method and the samples examined for planktic foraminifera biostratigraphy are available at <https://doi.org/xxxx>.

The Miocene of the Mediterranean was a time of changing tectonic setting, climate and eustatic sea level (e.g. Hüsing *et al.*, 2009; Robertson *et al.*, 2012; Herold *et al.*, 2012). The global climate cooled slightly during the Early Miocene, followed by major warming (~4 °C rise) related to the onset of the Middle Miocene Climate Optimum (MMCO) (c. 17 Ma) (Zachos *et al.*, 2001; Westerhold *et al.*, 2005; Zachos *et al.*, 2008; Miller *et al.*, 2020). The MMCO was followed (c. 14.8 Ma) by three-step cooling related to the Middle Miocene Climate Transition (MMCT), after which the global and Mediterranean climates are believed to have remained relatively cool (Kennett *et al.*, 1975; Flower & Kennett, 1994; Holbourn *et al.*, 2005; Miller *et al.*, 2005; John *et al.*, 2011; Miller *et al.*, 2020). The global changes are likely to have influenced the Mediterranean to some extent, including the nucleation, growth and demise of coral reefs. However, the effects of the MMCO, especially on reef-building organisms in the Mediterranean remains unclear (Bosellini & Perrin 2008).

During the Early to Middle Miocene, the Eastern Mediterranean Sea was influenced by the closure of the Southern Neotethys and the collision of the Arabian and Tauride continental units in SE Turkey-Iran. This resulted in a reduction and eventual loss of the marine connection between the Southern Neotethys and the Indian Ocean (Hüsing *et al.*, 2009; Robertson *et al.*, 2012, 2016). During the Late Miocene, the connection between the W Mediterranean and the Atlantic Ocean was also lost, resulting in the Late Miocene (Messinian) salinity crisis (Hsü *et al.*, 1973; Meilijson *et al.*, 2019).

Coral reefs and associated carbonate facies are key indicators of environmental change (Kleypas *et al.*, 2001; Kiessling, 2009). Miocene reefs developed in many areas of the Mediterranean (Esteban, 1979, 1996; Franseen *et al.*, 1996; Perrin & Bosellini, 2012) (Fig. 1), including: Cyprus (e.g. Eaton & Robertson, 1993; Follows, 1992), Crete (e.g. Brachert *et al.*, 2006), Israel (e.g. Buchbinder *et al.*, 1993), S Turkey (e.g. Janson *et al.*, 2010; Pomar *et al.*, 2012; Vescogni *et al.*, 2014), S Spain (e.g. Brachert *et al.*, 1996; Pomar *et al.*, 1996; Braga & Aguirre, 2001), Corsica and Sardinia (e.g. Benisek *et al.*, 2009; Tommasetti *et al.*, 2013), Northern Italy (e.g. Chevalier, 1962); Central Italy (e.g. Bossio *et al.*, 1996); S Italy (e.g. Bosellini *et al.*, 2001; Bosellini *et al.*, 2002; Bosellini, 2006; Braga *et al.*, 2009; Pomar *et al.*, 2012), Malta (e.g. Pedley, 1979) and N Africa (e.g. Esteban, 1979, 1996; Saint Martin & Rouchy, 1990). An understanding of reef growth and demise throughout the Mediterranean is dependent on robust age controls that can be obtained using a combination of biostratigraphy and Sr isotopes, as undertaken here.

Miocene coral reefs and related facies are exposed around the northern, eastern and western margins of the Late Cretaceous Troodos ophiolitic massif (Henson *et al.*, 1949, Bagnall, 1960; Bear, 1960; Gass, 1960; Morel, 1960; Gass & Masson-Smith, 1963; Robertson, 1977a)

(Fig. 2). Previous research has shown that two phases of reef development existed, based mainly on evidence from SE and NW Cyprus, namely the Early Miocene Terra Member and the Late Miocene Koronia Member of the Miocene Pakhna Formation (Follows & Robertson, 1990; Follows, 1992; Follows *et al.*, 1996) (see below). The Early Miocene phase of reef development and related facies is best developed in SE Cyprus, near Cape Greco. Late Miocene reef and related facies are exposed *c.* 10 km to the west, near Cape Pyla (Constantinou, 1995; Follows, 1992). Here, we focus on the Early and Late Miocene reefs and related facies exposed in the less-known but important area of NW Cyprus (Fig. 1).

Our main objective here is to develop an improved chronostratigraphy for the Miocene reef-related deposits of NW Cyprus that can be used to shed light on reef growth and demise. We utilise a combination of biostratigraphy based on calcareous nannofossils, benthic foraminifera and planktic foraminifera, together with chemostratigraphy utilising Sr isotopes. Our specific aims are: (1) To improve the stratigraphy as depicted on the geological map of NW Cyprus (Constantinou, 1995); (2) To understand better the timing of the two phases of Miocene reef and reef-related facies; (3) To make chronostratigraphically-based comparisons of the dated facies in NW Cyprus with the Miocene reefs and related facies in SE Cyprus and elsewhere in the Mediterranean region, and (4) To assess the likely controls of the two-phase reef and related facies development. This is part of a wider study of the sedimentary development of the latest Cretaceous-Cenozoic of west Cyprus, currently being undertaken by the second author (Balmer).

Regional geological setting

Southern Cyprus is dominated by the Troodos ophiolite that formed by Supra-Subduction Zone spreading during the Late Cretaceous, c. 90 Ma (e.g. Pearce & Robinson, 2010). In our main area of interest, NW Cyprus, the crustal ‘basement’ beneath the Cenozoic stratigraphy was formed during the latest Cretaceous by the tectonic juxtaposition of the Late Cretaceous ophiolite with the Mesozoic continental margin/oceanic lithologies of the Mamonia Complex (e.g. Robertson & Xenophontos, 1993). This was accompanied by localised accumulation of Maastrichtian-aged polymict debris-flow deposits (Kathikas Formation) (Swarbrick & Naylor, 1980) (Fig. 3). The pre-Cenozoic ‘basement’ includes Early Campanian to Mid-Maastrichtian-aged volcanoclastic sedimentary rocks of the Kannaviou Formation (Robertson, 1977b; Chen & Robertson, 2019). Maastrichtian-Paleogene pelagic carbonates of the overlying Lefkara Formation are mapped in the south of the area (Fig. 3), whereas Miocene marine carbonates of the Pakhna Formation are developed more widely throughout western Cyprus (Constantinou, 1995). Pliocene-Early Pleistocene marine sediments are mainly exposed within a N-S neotectonic basin, known as the Polis graben (Robertson, 1977b), while Pleistocene non-marine sediments occur near the coast (Balmer *et al.*, 2019) (see Fig. 2).

Based on structural and sedimentary studies (Elion, 1983; Payne & Robertson, 1995, 2000; Kinnaird & Roberson, 2013), the Polis graben has been interpreted as a rift basin that mainly formed during the Mid-Late Miocene, with extension continuing into Pliocene and Pleistocene. The rift is inferred to have developed above a subduction zone that, in this area, generally dipped eastwards, related to late-stage contraction of the Southern Neotethys. Structural work indicates that pervasive, rectilinear high-angle extensional faulting characterises the rift flanks (Payne & Robertson, 1995, 2000) and extends eastwards across the periphery of the Troodos ophiolite and its sedimentary cover (Chen & Robertson, 2018; their supplementary material). Recently, an alternative model has been proposed in which the

Polis graben is interpreted as a piggy-back basin above blind thrusts (Papadimitriou *et al.*, 2018). Deep well and/or seismic reflection data would be needed to test this model. The long-standing interpretation of the Polis graben as a Neogene extensional basin is, however, retained here.

The Miocene reefs and related facies in SE Cyprus (Fig. 2) are developed on a relatively elevated platform (Follows *et al.*, 1996), which largely conceals their relationship to the Miocene succession as a whole. In contrast, in NW Cyprus, both the Early and the Late Miocene reefs and related facies can be stratigraphically linked to the development of deeper-water facies within the Polis graben (Fig. 2). Dating of these deeper-water facies can, therefore, shed light on the timing of reef growth and demise (Cannings, 2018).

The Miocene deposits of the circum-Troodos succession, including the Polis graben, are traditionally mapped as the Pakhna Formation (Henson *et al.*, 1949; Constantinou, 1995). The contact between the Maastrichtian-Paleogene Lefkara Formation and the Neogene Pakhna Formation is inferred to be diachronous, both in S Cyprus (Eaton & Robertson, 1993) and W Cyprus (Banner *et al.*, 1999; BouDagher-Fadel & Lord, 2006). The Miocene Pakhna Formation in W Cyprus, as elsewhere, is dominated by hemipelagic carbonates and redeposited neritic carbonates. The Early Miocene Terra Member, as defined here, is constituted of very localised exposures of *in situ* reefs, together with more widespread exposures of related, redeposited facies. The Late Miocene Koronia Member is made up of locally developed *in situ* patch reefs, together with large volumes of redeposited, neritic-derived carbonates. The remainder of the Miocene succession is here termed, Pakhna Formation (undifferentiated).

In W Cyprus, the Early Miocene phase of reef development has been dated, generally as Burdigalian, mainly based on benthic foraminifera from associated carbonate facies (Follows *et al.*, 1996). The Early Miocene reefs were inferred to have formed prior to a phase of extensional faulting that initiated the Polis graben (Payne & Robertson, 1995, 2000). The Late Miocene phase of reef development was dated, generally as Tortonian, again mainly based on associated benthic foraminifera (Follows *et al.*, 1996). This later phase of reef development was interpreted as being coeval with the main phase of extensional faulting that created the Polis graben (i.e. syn-rift facies) (Payne & Robertson, 1995, 2000; Kinnaird & Robertson, 2013).

Previous dating

All of the available Sr isotope and biostratigraphic dates come from associated facies rather than from the reef frameworks and thus the ages of the reefs are inferred indirectly.

In SE Cyprus, benthic foraminiferal biostratigraphy, supported by some planktic foraminiferal and calcareous nannofossil biostratigraphy of spot samples, has indicated an Aquitanian-Burdigalian age for the Terra Member, near Cape Greco (Follows, 1992; Follows *et al.*, 1996). A small number of samples from the Terra Member in NW Cyprus suggested a similar age range, based on calcareous nannofossil biostratigraphy (Follows *et al.*, 1996). Benthic foraminiferal assemblages, together with some planktic foraminiferal assemblages, have been identified from seven sections in NW Cyprus, five of which are in our study area (Drousha-Kritou Terra, Kinousa, Kritou Terra, Pano Arodes and Terra sections), and ages were determined ranging from Aquitanian to Late Burdigalian (Banner *et al.*, 1999). An Aquitanian-Burdigalian age for the Terra Member was later confirmed using additional sections in the Akamas Peninsula, to the south of our study area (BouDagher-Fadel & Lord,

2006). Recently, *Sphenolithus heteromorphus*, *Helicosphaera ampliaperta*, and *H. scissura* were identified in calcirudites in the Pegeia area of W Cyprus, suggesting correlation of this outcrop with the Early Miocene Terra Member (Papadimitriou *et al.*, 2018). In addition, benthic foraminifera have been used to indicate a Late Miocene age for the Koronia Member in both SE and NW Cyprus (Follows, 1992; Follows *et al.*, 1996). In particular, *Borelis sp.* was noted in the Koronia Member (Follows *et al.*, 1996) and was taken to support a Late Miocene age (Follows, 1992; Follows *et al.*, 1996).

Methods

Reconnaissance geological mapping

To provide a framework for our new dating results, the existing geological maps of NW Cyprus were utilised and, where appropriate, revised. Our main resources were the 1:250,000 Geological Map of Cyprus (Constantinou, 1995), a recent geological map of the Pliocene-Pleistocene in the northern Polis graben (Balmer *et al.*, 2019), and our own reconnaissance fieldwork. As a result, several new outcrops of Miocene-aged sediments were recognised and some existing outcrops and their stratigraphical contacts were re-assigned, mainly to the Pliocene (Fig. 3).

Sedimentary logging

To support our new dating, several well-exposed successions of the Pakhna Formation, representing both relatively proximal and more distal facies relative to the reefs, were selected and logged in detail (Fig. 6, logs 1-5). Representative samples were collected,

mainly for age determination. We focused on sections in which pelagic facies (chalk) or hemipelagic facies (marl; i.e. calcareous mudstone containing clay and/or silt) are intercalated with redeposited facies, of potentially Terra Member or Koronia Member material.

Dating

Calcareous nannofossils

Thirty samples from the Pakhna Formation were studied, mainly to refine the ages of the hemipelagic background sediments throughout the northern Polis graben area (Fig. 5) (see Supplementary Material for GPS locations). The calcareous nannofossils were identified using smear slides prepared using the standard smear method (Backman & Shackleton, 1983; Henderiks & Törner, 2006), and then examined with a light microscope at a magnification of x1000-1250. The calcareous nannofossil biostratigraphy is based on Backman *et al.* (2012) (see Table S2).

Benthic foraminifera

Benthic foraminifera were examined from two localities in the northwest of the Polis graben (Fig. 5), both as individual specimens and in orientated thin sections. Samples were soaked in water, then washed through a 32 µm sieve and dried. For orientated thin sections, individual specimens were separated from the host rock, mounted in epoxy resin and abraded with silicon carbide in order to expose the equatorial layer and the embryonic apparatus. The specimens were then fixed to a standard thin section slide using UV-sensitive Loctite glue;

excess material was removed by polishing. The resulting thin sections were observed using a polarising transmitted light microscope (at 120x and 400x magnification). Identification of the mounted specimen was based on the biometric parameter of the embryo, following the taxonomy proposed by Özcan & Less (2009) and Özcan *et al.* (2010). The results were compared to the biozones of Cahuzac & Poignat (1997).

Planktic foraminifera

Sixty samples of planktic foraminifera from selected locations (localities are listed in Supplementary Material, Table S3) were soaked in water for 24 hours and then washed over a 63 µm sieve in order to remove clay and silt grain matrix. Foraminiferal residues were dry-sieved using 150 µm, 250 µm and 355 µm-sized sieves and split into aliquots of ≈200 specimens per size fraction. The biostratigraphy utilises the biozones of Wade *et al.* (2011) and the stratigraphy of both Iaccarino *et al.* (2011) and Lirer *et al.* (2019).

Strontium isotopes

Planktic foraminifera were picked from 19 samples of undifferentiated Pakhna Formation, and also from marl horizons associated with reef deposits throughout the northern Polis graben (Fig. 5) (see Supplementary Material for GPS locations). The isotopic analysis was carried out using a VG-Sector-54 thermal ionization mass spectrometer in order to establish ⁸⁷Sr/⁸⁶Sr ratios. Strontium isotopic ages were calculated using the LOWESS Sr isotope Look-Up Table (Version 4: 08/04) (McArthur *et al.*, 2001; McArthur & Howarth, 2004). The total combined errors were calculated from a combination of empirical instrumental errors, the

226 analytical errors and the errors resulting from the LOWESS Sr curve (McCay *et al.* 2013; see
227 Supplementary Material).

228 **Results**

229 Stratigraphy

230 The reconnaissance geological mapping (Fig. 3), supported by the new age data (see below),
231 allows four facies of the Pakhna Formation to be distinguished. The first facies is redeposited
232 sediments, correlated with the Early Miocene Terra Member (in situ reefs are minimal; see
233 below). The second is redeposited sediments of the Koronia Member of Mid-Late Miocene
234 age, the third is *in situ* reefs of the Koronia Member also of Mid-Late Miocene age and the
235 fourth is undifferentiated Pakhna Formation, mostly marl and chalk.

236 The Miocene successions in NW Cyprus differ on both flanks and in the depocentre of the
237 Polis graben (Fig. 6). All of the units of the Pakhna Formation are exposed on the west flank
238 of the graben (although not as a continuous succession), whereas only undifferentiated
239 Pakhna Formation and the Koronia Member are exposed on the eastern flank. The
240 intervening basin depocentre is restricted to the undifferentiated Pakhna Formation. A
241 representative E-W cross-section of the Polis graben (modified from Payne & Robertson,
242 1995) (Fig. 7) shows that the outcrops of the reefs and related facies are structurally
243 controlled. In particular, the Terra and Koronia members are exposed in different fault blocks
244 on the western flank of the graben.

245 In NW Cyprus, the Terra Member reef facies was only found exposed *in situ* in one very
246 small area on the upper NW flank of the graben, near Androlikou (Figs. 3, 8E). This
247 exposure, numerous reworked reef blocks in the vicinity, and associated talus deposits have a
248 relatively high biodiversity of corals, including *Tarbellastraea*, *Porites* and *Favia* (Follows *et*
249 *al.*, 1996). The Terra Member as a whole is dominated by reef-derived talus, mostly debris
250 flow-deposits, as well exposed on the upper eastern slopes of the Akamas Peninsula in the
251 key Kourroulla Gorge section (named after the stream course at the northern end of the
252 gorge) (Fig. 3).

253 In NW Cyprus, *in situ* reef and closely related facies of the Koronia Member are exposed on
254 the western flank of the graben, represented by circular to elongate exposures, typically up to
255 100s of m long and up to *c.* 20 m thick, mainly located near the crest of the northern Akamas
256 Peninsula (Fig. 3). The Koronia Member is also widely distributed, mainly as redeposited
257 material, along the upper, eastern slopes of the graben, typically as elongate depositional
258 units, up to *c.* 7 km long by 30 m thick (e.g. near Pelathousa) (Fig. 3).

259 The Koronia Member reef is dominated by poritid corals (Fig. 8F) which are often poorly
260 preserved, associated with calcareous algae, benthic foraminifera, serpulids, echinoids and
261 other neritic fauna (Follows *et al.*, 1996). Locally (e.g. near Steni) (Fig. 3), on the NE graben
262 flank, the upper surface of the reefal material is karstified and dissected by neptunian fissures
263 that are locally infilled with marl (Fig. 8G), which was dated as Pliocene (see below).
264 Pliocene marl deposits stratigraphically overlie the neptunian fissures on the NE graben
265 flank. Many of these high-elevation Pliocene deposits on the east flank are cut by high-angle
266 extensional faults (orientated approximately NNE-SSW).

268 A continuous vertical succession is very well exposed in Kourroulla Gorge, NW Akamas
269 Peninsula (Figs. 3; 7, log 1). This begins with matrix-supported conglomerates (calcirudites),
270 interpreted as debris-flow deposits; these contain abundant clasts of benthic foraminiferal
271 packstone/grainstone, rhodoliths and reworked reef material. The clasts within the matrix-
272 supported conglomerate are interpreted to have been derived from the Terra Member, based
273 on their composition, including several types of coral characteristic of the Terra Member
274 reefs (*Tarbellastraea*, *Porites* and *Favia*). Overlying well-bedded marl, normal-graded
275 calcarenites and matrix-supported conglomerates (calcirudites) contain contrasting material
276 typical of the Koronia Member, including poritid coral and calcareous algae. Assuming these
277 stratigraphic correlations are correct, dating of the relatively fine-grained marl between the
278 Terra versus Koronia member-derived material could indicate when Terra Member reef
279 development ended and Koronia Member reef development started, and also the time that
280 elapsed between these two events.

281 Two shorter successions that were measured on the eastern flank of the graben (Pano
282 Akouradelia sections A & B) (Fig. 4, logs 2 and 3) also contain coarse coral debris and could,
283 therefore, help to date when carbonates (Terra Member and/Koronia Member) were
284 redeposited from the adjacent reefs. An additional succession of fine-grained sediments that
285 includes organic carbon-rich layers (potential sapropels) (Pano Akouradelia section C) (Fig.
286 4, log 4) was inferred to represent a relatively high (young) part of the Pakhna Formation and
287 might, as a result, shed light on the final Late Miocene reef demise (Koronia Member), prior
288 to the Messinian salinity crisis.

In addition, representative of the Miocene succession on the eastern flank of the graben, a long, intact section of redeposited carbonates was logged near Evretou Dam (Fig. 4, log 5). Based on its composition, including poritid coral debris, these deposits were previously correlated with the Koronia Member (Payne & Robertson, 1995; Constantinou, 1995).

Chronology

Calcareous nannofossils

Samples of redeposited sediments from the west flank of the graben that include Terra Member reef material contain Early to Middle Miocene nannofossils (Table S2). Samples taken from above (TC1787) and below (TC1786) the last calcirudite (debris flow) bed at the base of the section in Kouroulla Gorge (Fig. 8A, B, C, D, Fig. 4, log 1) are dated as 13.53-13.9 Ma (biozone CNM7) (based on the presence of *Sphenolithus heteromorphus*) (Fig. 9).

Samples from the east flank of the graben (TC1768, 80), previously mapped as Late Miocene Koronia Member (Payne & Robertson, 1995; Constantinou, 1995) were found to contain nannofossil assemblages of Pliocene age (biozones CNPL1-CNPL4) (5.36 Ma – 2.76 Ma) (Table S2), indicating that in this case the coral debris was reworked long after reef growth ended.

Benthic foraminifera

Three samples that contain abundant, well-preserved large benthic foraminifera (LBF) were studied from the west flank of the graben (Fig. 10). The most LBF-rich sample, from the central western flank of the graben (*c.* 2.5 km S of Neo Chorio) (TC1749), is characterized by *Nephrolepidina praemarginata*, *Nephrolepidina morgani*, *Eulepidina* sp. *Heterostegina* cf. *borneensis* and *Amphistegina* sp., together with probable *Operculina* sp., and also *Nummulites* sp. This assemblage, taking account of the absence of *Miogypsina* sp. and

312 *Miogypsinoidea* sp, suggests an Early Chattian (Late Oligocene) age, and can be assigned to
313 the Shallow Benthic Zone 22B of Cahuzac & Poignant (1997).

314 Two additional samples from the northern Akamas Peninsula (c. 2.5 km NW of Akamas)
315 (TC1746 and TC1747) (Fig. 10) contain a different faunal assemblage, characterized by
316 abundant miliolids, including the age-diagnostic species *Borelis melo melo*; while, large
317 rotalids such as *Nephrolepidina* and *Myogypsina* are absent. The assemblage suggests a
318 Middle to Late Miocene age; i.e. earliest Langhian, c. 16 Ma to Mid-Messinian, c. 6 Ma
319 (Cahuzac & Poignant, 1997). The two samples also contain common *Dendritina* sp., which,
320 together with *Borelis melo melo*, suggest a Late Miocene age (Betzler & Schmitz, 1997).

321 *Planktic foraminifera*

322 60 samples were studied (see supplementary material for sample locations and characteristic
323 assemblages). Based on age-diagnostic species four distinct planktic foraminiferal
324 assemblages can be identified, indicating specific time intervals: (1) A Middle Miocene
325 assemblage characterised by *Orbulina universa*, *Globoquadrina* spp, *Paragloborotalia*
326 *siakensis* & *Orbulina suturalis*; (2) A Late Miocene-Early Pliocene assemblage characterised
327 by *Globorotalia margaritae*, *Sphaeroidinellopsis seminulina*, *Globoturborotalita nepenthes*
328 & *Neogloboquadrina acostaensis*; (3) A Late Pliocene assemblage characterised by *O.*
329 *universa*, *Globigerinoides ruber*, *Sphaeroidinella dehiscens* & *Globigerinoides extremus*; (4)
330 An Early Pleistocene assemblage characterised by *O. universa*, *G. ruber* & *S. dehiscens* (see
331 Supplementary Material Table S3). The foraminiferal ages are used to support the results
332 from the other dating methods (rather than as a stand-alone technique) because of the absence

of many key age-diagnostic species in the Mediterranean and the relatively low temporal precision of planktic foraminifera biozones in the Miocene (Lirer *et al.*, 2019).

Strontium isotopes

New Sr isotope dates (19 samples) are summarised in Figure 11. For the Kouroulla Gorge section on the west flank of the graben (Fig. 4, log 1) an age of *c.* 9.3 Ma was obtained for a sample from near the top of the marl sequence (TC1792), directly beneath the coarse redeposited facies correlated with the Koronia Member. For the reference section on the eastern flank, near Evretou Dam (Fig. 4 log 5), a marl sample (TC17122) between beds of reef-derived material gave an age of *c.* 6.1 Ma, confirming correlation with the Koronia Member. In addition, samples (TC1705, 09, 10, 13 68, 69, 79) collected from exposures on the east flank of the graben yielded Pliocene and Pleistocene ages, supporting the remapping of these sections (Fig. 3). An Early Pliocene age (*c.* 5.2 Ma) was obtained for a sample of pink marl that infills the neptunian fissures on the karstified, uppermost surface of the limestone correlated with the Koronia Member (Fig. 8G).

Discussion

Chronology and palaeo-environments of deposition

Our new dating, when integrated with existing data, indicates a revised timing of reef and reef related facies development in NW Cyprus (Fig. 12).

Oligocene to Early Miocene

352 Assemblages of benthic foraminifera that are dominated by a diverse fauna of large rotalids,
353 similar to the Early Chattian assemblage determined here, occur widely within shallow-water
354 carbonates of Late Oligocene and Early Miocene age elsewhere in the Tethyan region (e.g.
355 Matteucci & Schiavinotto, 1977; Bosellini *et al.*, 1987; Bosellini & Perrin, 1994; Özcan *et*
356 *al.*, 2009; Tomassetti *et al.*, 2013; Pomar *et al.*, 2014; Coletti *et al.*, 2018, 2019). Our Early
357 Chattian benthic foraminifera come from a localised (isolated) exposure (≈ 1 m across) near
358 the crest of the Akamas Peninsula (Fig. 5). This is part of an outcrop that was previously
359 included within foraminifera-rich calcarenites of the Terra Member (Follows *et al.*, 1996).
360 The material is reworked within debris flow-deposits. Pelagic sediments of Oligocene age
361 were previously identified in W Cyprus near Paphos (Fig. 2), directly SW of the Geroskipou
362 exit of the A6 highway (BouDagher-Fadel & Lord, 2006). The presence of Late Oligocene
363 benthic foraminifera, therefore, indicates the former existence of a shallow-water carbonate
364 shelf (of unknown dimensions) near the present crest of the northern Akamas Peninsula.

365 Our Early to Middle Miocene ages of nannofossils from the western flank of the graben in
366 Kouroulla Gorge (Table S2) are consistent with derivation from the Terra Member reefs that
367 were previously dated as Aquitanian-Burdigalian in the Akamas Peninsula, using benthic
368 and/or planktic foraminifera (Follows *et al.*, 1996; BouDagher-Fadel & Lord, 2006). The
369 inferred Oligocene carbonate platform could have provided a suitably firm foundation for the
370 Early Miocene reefs. Based mainly on the evidence of the coarse redeposited facies, one or
371 more patch reefs, with diverse coral species, developed near the present crest of the NW
372 Akamas Peninsula during the Early Miocene (Fig. 13A). The presence of clasts of benthic
373 foraminiferal packstone/grainstone, rhodoliths (in addition to Terra Member corals) within
374 the redeposited material (e.g. Kouroulla Gorge) (Figs. 3, 8B, C, D; 7, log 1) suggest that the
375 patch reefs were fringed by rhodoliths and benthic foraminiferal shoals, as inferred in both

SE Cyprus (Follows, 1992) and NW Cyprus (Follows *et al.*, 1996). Additional neritic facies accumulated further south, including the Pegeia area. However, elsewhere in W Cyprus chalk and marl deposition (undifferentiated Pakhna Formation) persisted during the Early Miocene, indicating areas where water depths were too great or where the substratum was unsuitable for reef growth.

Middle Miocene

There is no facies or age evidence of continued reef development during the Middle Miocene anywhere in Cyprus. Along the NW flank of the Polis graben, debris flow-deposits were eroded from the pre-existing Early Miocene reefs and related facies (Terra Member) and accumulated within adjacent hemipelagic deposits, as exposed in Kouroulla Gorge (Fig. 8B, C, D, 7, log 1). Farther south in the Akamas Peninsula, at Pano Akourdalia and Pano Arodes (Fig. 4, logs 2, 3), marl samples (undifferentiated Pakhna Formation) gave Langhian-Serravalian ages (Table S2) corresponding to biozones mid CNM7- CNM8 (i.e. 14.86 Ma - 12.57 Ma). This suggests that the western flank of the Polis graben (at least the southern part) remained in relatively deep water during the Mid-Miocene. In addition, hemipelagic sedimentation (undifferentiated Pakhna Formation) continued near the basin depocentre (Figs. 4, 5), as is indicated by the Langhian (CNM7) age of sample TC17143 (hemipelagic marl), collected c. 2 km ESE of Androlikou.

Late Miocene

Most of our Koronia Member samples lack age-diagnostic microfossils or are unsuitable for dating because of recrystallisation. However, two samples from the west flank of the graben

in the Akamas Peninsula (approximately north east of Akamas Village) (Fig. 10) (TC1746 and TC1747) contain Middle-Late Miocene benthic foraminiferal assemblages. A Late Miocene age is very likely for these samples due to the association of *Dendritina sp.* with *Borelis melo melo*, and thus confirms the mapping as part of the Koronia Member.

Some bioclastic calcarenites (packstones/grainstones) on the east flank of the graben (e.g. near Pelathousa) were previously mapped as the Early Miocene Terra Member based on apparent facies similarities (Payne & Robertson, 1995). However, one sample (TC17122) of calcareous mudstone from an interval located between bioclastic calcarenites and calcirudites (including coral reef talus) in the Evretou Dam section (Fig. 4, log 5) yielded calcareous nannofossils of Late Miocene age (biozones CNM11-CNM20). This sample was also dated at *c.* 6.1 Ma using Sr isotopes (Fig. 11), again confirming a correlation with the Koronia Member. Early Miocene neritic facies have not been confirmed along the eastern flank of the graben. The *c.* 6.1 Ma age also suggests that the Koronia Member reef development persisted into the earliest Messinian, longer than previously assumed (Follows *et al.*, 1996).

During the Late Miocene, patch reefs developed on both the western and eastern flanks of the Polis graben, dominated by a poritid corals, together with marginal benthic foraminifera and rhodolith-rich facies (Follows *et al.*, 1996) (Fig. 13B). Extensional faulting was highly active during the Late Miocene (Payne & Robertson, 1995). The resulting tilted and uplifted fault blocks were ideal for patch reef development, as along the northern margin of the Troodos Massif (Follows and Robertson 1990; Follows *et al.*, 1996). Debris flow-deposits and calciturbidites infilled the structurally-controlled sediment accommodation space surrounding the patch reefs, with more distal facies reaching the depocentre of the Polis graben (although this is mostly concealed by Pliocene sediments).

During the Messinian salinity crisis (Hsü *et al.*, 1973; Meilijson *et al.*, 2019), gypsum and related facies accumulated within a roughly circular depocentre in the south of the Polis graben (c. 20 km in diameter), known as the Polemi basin (Robertson, 1977a; Orszag-Sperber *et al.*, 1989, 2009; Manzi *et al.*, 2016). In contrast, the uplifted flanks of the graben were subaerially exposed and locally karstified, as observed locally on the east flank (e.g. SE of Pelathousa). Elsewhere, Miocene sediments were eroded to form small volumes of fluvial sediments (e.g. at Evretou Dam) (Robertson, 1998a; Kinnaird & Robertson, 2013).

Pliocene

Pinkish marl (TC1705 – c. 5.2 Ma) that locally infills neptunian fissures (Fig. 8G) in the erosional surface of the Koronia Member on the east flank of the Polis graben was dated as Pliocene using planktic foraminiferal and Sr isotope dating and can, therefore, be correlated with the Nicosia Formation (Fig. 6). The presence of neptunian fissures extending down beneath a karstified surface confirms that subaerial exposure took place during the Messinian salinity crisis.

In response to earliest Pliocene (Zanclean) re-flooding of the Mediterranean (Hsü *et al.*, 1973; Spezzaferri *et al.*, 1998; Iaccarino *et al.*, 1999; Spezzaferri & Tamburini, 2007), Pliocene marine marls with a rich neritic shelly fauna progressively covered the Messinian land surface. The karstified erosion surface on the Koronia Member (with neptunian fissures) was covered by c. 5.2 Ma. This timing suggests that deposition of the Nicosia Formation began on the NW flank of the graben c. 100 kyr earlier than previously envisaged (Balmer *et al.*, 2019). Deposition in the depocentre is likely to have begun slightly earlier than this.

441 Sediment burial proceeded generally from north to south, controlled by the overall graben
442 topography. The depocentre became more elevated southwards, beginning in Chrysochou
443 Bay to the NW of Polis, extending down the northern Polis graben, and across the former
444 Polemi basin until it terminated southwards (Balmer *et al.*, 2019). The northern graben
445 depocentre shallowed during the Late Pliocene (*c.* 2.76 Ma), initiating shallower-water
446 calcareous bioclastic sedimentation, which is correlated with the Athalassa Formation in its
447 type area, near Nicosia (Balmer *et al.*, 2019). The southern graben depocentre remains poorly
448 documented, however, NW Cyprus emerged during the Pleistocene, together with the
449 Troodos Massif and Cyprus as a whole (Kinnaird *et al.*, 2011; Palamakumbura *et al.*, 2016).

450 The distribution of sedimentary facies in relation to the mapped faults shows that crustal
451 extension continued during the Pliocene and Pleistocene to Recent (Payne & Robertson,
452 1995; Kinnaird & Roberson, 2013; Balmer *et al.*, 2019), contributing to the present
453 topography of the Polis graben. The relatively high elevation of some of the newly
454 discovered Pliocene exposures, especially on the east flank of the graben (i.e. sample TC1705
455 is currently at *c.* 150 m above sea level) suggests that extensive fault-controlled uplift
456 continued well into the Pliocene and possibly later. This late-stage faulting is supported by
457 the presence of numerous high-angle extensional faults (orientated NNW-SSE) cutting the
458 Pliocene deposits.

459 **Regional to global comparisons**

460 *Early Miocene reefs*

461 The relatively large outcrop of the Terra Member near Cape Greco in SE Cyprus is broadly of
462 the same age (Aquitanian-Burdigalian) as that in NW Cyprus (Fig. 2). Patch reefs, up to 80 m
463 thick and 500 m in diameter (Follows, 1992), made up of hermatypic z-corals (i.e. symbiont-
464 bearing sensu Bosellini & Perrin, 2008) developed on a tectonically stable platform, fringed
465 by shoal facies that were dominated by large benthic foraminifera, calcareous red algae
466 (rhodoliths) and echinoids (Follows, 1992).

467 In the western Mediterranean region, Early Miocene reefs and related facies, similar to those
468 of the Terra Member, are reported from Sardinia and Corsica (e.g. Galloni *et al.*, 2001;
469 Benisek *et al.*, 2009; Tomassetti *et al.*, 2013) (Fig. 1). The reefs in Corsica reach >1 km in
470 diameter and up to 12 m thick, and those in Sardinia > 350 m in diameter and up to 40 m in
471 thickness (Galloni *et al.*, 2001). As in Cyprus, the diverse coral assemblages of the reefs were
472 fringed by carbonate shoals with coralline algae, echinoids and large benthic foraminifera
473 (e.g. Galloni *et al.*, 2001; Benisek *et al.*, 2009; Tomassetti *et al.*, 2013). The Bonifacio Basin
474 in SE Corsica is remarkably similar in facies to the Terra Member (Follows *et al.*, 1996;
475 Tomassetti *et al.*, 2013; Brandano *et al.*, 2016). Similar Early Miocene carbonates also
476 accumulated on the Eratosthenes Seamount (open ocean), south of Cyprus (Fig. 2, inset). The
477 seamount is interpreted as a continental fragment that rifted from the North African-Arabia
478 continental margin, related to the opening of the Southern Neotethys (Robertson, 1998a;
479 Kempler, 1998). The successions on the crest and on the northern flank of the Eratosthenes
480 Seamount were drilled during Ocean Drilling Project Leg 160 (Hole 966F) (Emeis *et al.*,
481 1996). The Miocene sediments on the seamount accumulated on a relatively stable platform.
482 The Early Miocene, lower part of the succession is characterised by a diverse assemblage of
483 large benthic foraminifera and echinoids, remarkably similar to the shoals surrounding the
484 Early Miocene (Terra Member) patch reefs in SE Cyprus (Follows *et al.*, 1996) and on the

485 Eratosthenes Seamount south of Cyprus (Coletti *et al.*, 2019). These Early Miocene
486 carbonates are overlain by a Mid-Miocene succession, rich in coralline red algae, then by a
487 Late Miocene coral-rich interval, and finally by lagoonal facies (Robertson, 1998b; Coletti *et*
488 *al.*, 2019; Coletti & Basso 2020).

489 In the western Mediterranean region, close to major landmasses, z-corals mainly formed
490 small oligospecific bioconstructions (<5 m thick), as in Central Italy (Brandano, 2003;
491 Civitelli & Brandano, 2005). Similar small biogenic structures (characterised by high species
492 diversity) are inferred from reworked material, as in Northern Italy (Chevalier, 1962;
493 Bosellini & Perrin, 2008; Perrin & Bosellini, 2012) and in SW France (Oosterbaan, 1988). In
494 the Eastern Mediterranean region, again relatively close to land, relatively large (*c.* 1 km in
495 diameter by up to 100 m in thick) z-coral build-ups are known in the Mut Basin, Southern
496 Turkey (Bassant *et al.*, 2005; Pomar *et al.*, 2012). These reefs are dominated by poritid corals
497 (Bassant *et al.*, 2005) and become larger further away from the local sources of siliciclastic
498 sediment (Pomar *et al.*, 2012: Fig. 5). Sparse corals are also reported from the Early Miocene
499 of the Adana Basin (Gurbuz, 2015).

500 The Corsica, Sardinia, Cyprus and Eratosthenes Early Miocene carbonate systems all
501 developed away from major sources of siliciclastic sediment. This suggests that continental
502 run-off, represented by high siliciclastic input and high levels of nutrients (both supplied
503 fluvially) could have been detrimental to the Early Miocene carbonate factories, especially
504 those dominated by z-corals. On the other hand, some carbonate-secreting organisms, such as
505 coralline algae and benthic foraminifera, are known to survive even in sites of near-
506 continuous siliciclastic influx (Wilson & Lokier, 2002; Lokier *et al.*, 2009). For example,
507 small coral-algal builds-up developed in the Miocene Kaş basin, SW Turkey, which is

interpreted as a foreland basin in front of advancing thrust sheets (Hayward *et al.*, 1996). In general, however, settings away from high siliciclastic (and nutrient) influx excess nutrients appear to have favoured Early Miocene reef development.

Middle Miocene reefs

There is no record of Middle Miocene coral reefs or related facies in Cyprus. However, Middle Miocene reefs and related facies are known elsewhere in the Eastern Mediterranean, in Israel (Buchbinder *et al.*, 1993) and in the Mut basin (southern Turkey) (Vescogni *et al.*, 2014). Middle Miocene reef development was more common in the western Mediterranean region; e.g. in Hungary (Oosterbaan, 1990), Austria (Riegel & Piller, 2000), N Italy (Chevalier, 1962), Algeria (Belkebir *et al.*, 1994), France (Chevalier, 1962; Cahuzac and Chaix, 1996) and Spain (Calvet *et al.*, 1994; Braga *et al.*, 1996).

Late Miocene reefs

In its type area, Koronia Hill, and elsewhere along the northern margin of the Troodos Massif, the Koronia Member developed as patch reefs and related neritic facies on tilted fault blocks, up to 3 km long by 800 m wide (Follows & Robertson, 1990; Follows *et al.*, 1996). The Koronia Member is also exposed in southern Cyprus, at Happy Valley, as large (up to tens of m-sized) detached blocks within mega-debris flow deposits. These blocks are interpreted to have been derived from a bathymetric high to the south, within an area of *c.* 1.5 km² in the Akrotiri Peninsula (Fig. 2). This local high was created by regional compression which affected southern Cyprus during the Early Miocene (Robertson *et al.*, 1991; Eaton & Robertson, 1993). The reef material and related neritic facies accumulated on a small

529 shallow-water carbonate platform, followed by downslope collapse and reworking (probably
530 tectonically triggered). In addition, the presence of redeposited reef talus (poritid corals) and
531 reef-proximal facies (e.g. benthic foraminifera and red algae) within the Pakhna Formation,
532 around the southern periphery of the Troodos massif (e.g. near Tokhni), points to the
533 existence of Late Miocene fringing reefs that were later completely eroded (Robertson 1977a;
534 Eaton & Robertson, 1993).

535 In addition to *in situ* patch reefs, the Koronia Member includes abundant proximal,
536 redeposited gravity-flow facies, as exposed in the Polis graben, along the north flank of the
537 Troodos Massif (e.g. at Kottaphi Hill), at Happy Valley (S Cyprus) and along the southern
538 periphery of the Troodos massif (e.g. at Tokhni). Similarly, the Tortonian-Messinian Pattish
539 Formation, central Israel, is dominated by talus deposits that were derived from a *Porites*-
540 dominated shelf-edge reef that is no longer preserved (Buchbinder *et al.*, 1993; Buchbinder &
541 Zilberman, 1997).

542 The skeletal assemblage of the Koronia Member reefs is dominated by a monogeneric
543 poritid-dominated assemblage (Follows, 1992). Similar Late Miocene assemblages
544 characterise other depositional settings away from major land-masses, including the
545 Eratosthenes Seamount (Robertson, 1998b; Coletti *et al.*, 2019; Coletti & Basso, 2020), the
546 Salento Peninsula in southern Italy (e.g. Bosellini *et al.*, 2001; Bosellini *et al.*, 2002; Bosellini,
547 2006; Vescogni *et al.*, 2008), and the islands of Lampedusa (Grasso & Pedley, 1985) and
548 Majorca (Pomar *et al.*, 1996). Comparable reefs also developed in near-continent settings,
549 including Tuscany (Bossio *et al.*, 1996), Apulia (Bosellini *et al.*, 2001; Bosellini *et al.*, 2002)
550 and southern Spain (Esteban, 1996; Mankiewickz, 1996; Braga *et al.*, 2009). These poritid

reefs also developed in a range of tectonically stable and unstable areas suggesting that they were able to cope with a wide range of sedimentary settings (Esteban, 1979).

Controls of reef growth and demise in NW Cyprus

We now attempt to assess the possible controls of reef development that could be applicable to northwest Cyprus, including sea-level rise or fall (local, regional or global), sea-water temperature/climate, nutrients, salinity and tectonic instability.

The Early Miocene reefs

An overall warm climate appears to have favoured the northward latitudinal expansion of z-corals during the Early Miocene-Langhian throughout the Mediterranean (Perrin & Bosellini, 2012). Ocean temperatures rose globally during much of the Early Miocene, peaking during the Mid-Miocene Climatic Optimum (c. 17–14.50 Ma; Burdigalian-Langhian) (Zachos *et al.*, 2001; Zachos *et al.*, 2008; De Vleeschouwer *et al.*, 2017; Miller *et al.*, 2020). Water temperatures then generally decreased, corresponding to the growth of the East Antarctic Ice Sheet (c. 13.7 Ma; late Serravallian) (Kennet *et al.*, 1975; Flower & Kennett, 1994; Holbourn *et al.*, 2005; Miller *et al.*, 2005). Although Mid-Miocene reefs are absent in Cyprus, the Serravallian drop in temperature, appears to have damaged coral reefs across the Mediterranean region, as indicated by a decrease in relative abundance, size and diversity during this time (Zachos *et al.*, 2001; Bosellini & Perrin, 2008; Perrin & Bosellini, 2012; Prista *et al.*, 2015).

570 Taxonomic coral richness decreases after the Burdigalian in line with decreasing
571 temperatures in the Mediterranean region. Surprisingly, the Mid-Miocene Climatic Optimum
572 is not obviously recorded in z-coral generic richness (Bosellini & Perrin, 2008), suggesting
573 that temperature was not the sole control. Other possible controls include siliciclastic and
574 nutrient run-off (Mutti *et al.*, 1997; Brandano *et al.*, 2017). During the Early-Middle
575 Miocene, the Southern Neotethys between Arabia (North African plate) and the Taurides
576 (Eurasian plate) effectively closed (Aktaş & Robertson, 1984; Yılmaz, 1993; Rögl, 1999;
577 Hüsing *et al.*, 2009; Taylforth *et al.*, 2014). The collision was associated with very high
578 siliciclastic (and potentially nutrient) supply, as documented in SE Turkey (Lice Formation)
579 (e.g. Robertson *et al.*, 2016). Also, palaeoceanography (e.g. current systems) fundamentally
580 changed as water exchange between the Mediterranean and the Indo-Pacific was curtailed. As
581 a result, conditions may have become less favourable condition for z-corals.

582 Global (eustatic) sea-level change is another possible trigger of reef growth or demise. Sea-
583 level highstands have been suggested to trigger high carbonate production as reefs attempt to
584 keep up with rising sea-level (Schlager *et al.*, 1994; Schlager, 1999). However, the scope for
585 greatly increased upward carbonate growth is limited for small patch reefs, unlike large
586 carbonate platforms. Conversely, the absence of Mid-Miocene reefs in Cyprus (and
587 elsewhere) might represent coral growth not keeping up with eustatic sea-level rise or rapid
588 fluctuations (Robertson *et al.*, 1991). Modern reefs are generally capable of keeping pace
589 with eustatic sea-level changes, especially small ones (e.g. Toscano & Macintyre, 2003;
590 Toomey *et al.*, 2013).

591 The last (dated) debris-flow of Terra Member reef-derived material (13.53-13.9 Ma;
592 Serravallian-Langhian boundary) (Fig. 14). This deposition (Fig. 8B, C, D; 7, log 1), was

593 broadly contemporaneous with an isotopically-determined fall in global sea level of 50-60 m
594 (Miller *et al.*, 2005; John *et al.*, 2011; Miller *et al.*, 2020), which corresponded to the *c.* 13.7
595 Ma growth of the East Antarctic Ice Sheet (Kennet *et al.*, 1975; Flower & Kennett, 1994;
596 Holbourn *et al.*, 2005; Miller *et al.*, 2005).

597 Assuming the debris was derived directly from living reefs, then the end of the debris-flow
598 deposition could be interpreted as the demise of the reef; i.e. at *c.* 13.7 Ma. A sudden sea-
599 level fall could have exposed and killed off the reefs that were later eroded and reworked
600 downslope as talus (although as noted above modern reefs typically adapts to sea-level
601 change). However, it is very probable that the reefs died out earlier, around the Burdigalian-
602 Langhian boundary (*c.* 16 Ma), such that the inferred sea level/temperature fall at *c.* 13.7 Ma
603 only resulted in the reworking of dead coral and related talus. There are hints that this may be
604 the case. The debris includes consolidated marl and chalk (Miocene and older) suggesting
605 that this material is a second-cycle erosive product rather than having been shed directly from
606 living reefs. Only the end of debris-flow deposition was dated at *c.* 13.7 Ma, whereas
607 underlying debris-flows could be older and relate to previous sea-level falls or tectonic
608 effects. Also, carbonate platform low-stand detritus, as documented elsewhere, is mainly thin,
609 channelized lithic breccias with erosional debris that was derived from the by-then
610 subaerially exposed reefs, as seen in the Late Eocene-Oligocene Maiella carbonate platform,
611 Italy (Vecsei & Sanders, 1997). This contrasts with the relatively thick, lenticular and
612 heterogeneous Mid-Miocene debris-flows in NW Cyprus. More dating of clasts in the other
613 debris flows would help to test the alternatives.

614 Regional-scale tectonics are also known to have strongly influenced carbonate platforms
615 during the Cenozoic (Bosence, 2005). The Langhian was characterised by tectonically-

616 controlled deepening and marine transgression throughout many parts of the eastern
617 Mediterranean region, including southern Turkey, namely the Köprü Basin (Flecker *et al.*,
618 2005), the Manavgat Basin (Flecker *et al.*, 1995), the Mut Basin (Şafak *et al.*, 2005), and the
619 Adana Basin (Gurbuz, 1999; Gurbuz, 2015), and the Hatay Basin, northern Syria
620 (Hardenberg & Robertson, 2007). On the Eratosthenes Seamount a Mid-Miocene sea-level
621 rise (not fall) has been inferred, related to a switch from the Early Miocene diverse large
622 benthic foraminiferal and echinoid assemblage, to the Mid-Miocene faunally impoverished
623 coralline red algal assemblages (Coletti *et al.*, 2019). Supporting evidence includes: 1. A
624 decrease in shallow-water bioclasts including corals, thick-shelled large benthic foraminifera
625 (e.g. *Amphistegina*); 2. An increase in planktic foraminifera and deep-photoc-zone benthic
626 foraminifera (e.g. thin-shelled *Heterostegina*); 3. A shift from shallow water to relatively
627 deep-water coralline algae (Coletti *et al.*, 2019; Coletti & Basso, 2020). The overall driver of
628 the inferred tectonic subsidence, including the Eratosthenes Seamount, was the convergence
629 of the African and Eurasian plates that led to rapid flexural subsidence (e.g. Robertson, 1990;
630 Coletti *et al.*, 2019).

631 Local-scale tectonics could also play a role in the reef demise. The Early Miocene Terra
632 Member carbonate platform developed on a high, representing a precursor to the modern
633 Akamas Peninsula (Fig. 13A). Reef development appears to have preceded the main phase of
634 rifting of the Polis graben (Payne & Robertson, 1995; Follows *et al.*, 1996). However, when
635 exactly the rifting began remains uncertain. Initial rifting could have destabilised the reefs
636 and triggered the mass-wasting of talus, including the Mid-Miocene debris flow-deposits, as
637 seen on the NW flank of the Polis graben in Kouroulla Gorge (Fig. 8B, C, D 7, log 1). These
638 debris-flow deposits include clasts of benthic foraminiferal packstone/grainstone, reef debris,
639 Pakhna Formation marl and older, Lefkara Formation chalk indicating relatively deep-level

erosion that is likely to have resulted from tectonic uplift. The uppermost debris-flow deposits in the Kouroulla Gorge section (Fig. 4, log 1) continue to include Terra Member coral material. Marls above and below this redeposited unit contain Mid-Miocene (*c.* 13.53–13.9 Ma; Serravallian) (Table S2) calcareous nannofossils indicating that reef material continued to be redeposited until *c.* 13.7 Ma, although, as noted above, this may well have post-dated the death of the reefs. In any case, local tectonics are unlikely to have controlled the demise of the Early Miocene reefs because the reefs in SE Cyprus developed (and remained) on a relatively stable platform.

In summary, no single cause convincingly explains the end of Early Miocene (*c.* 16 Ma) reef development in Cyprus and some other areas of the Mediterranean. Instead, the individual reefs in different areas are likely to have experienced different combinations of controls; *i.e.* glacio-eustatic global sea-level/temperature fall, variable siliciclastic/nutrient input, changed current strength/distribution, regional tectonic subsidence, and local tectonic uplift/subsidence. In other words, around the end of the Burdigalian, the reefs in Cyprus and in many other areas seem to have faced a ‘perfect storm’ that they did not survive.

The Late Miocene reefs

Our Sr isotope dating suggests that the Koronia Member reef-phase in NW Cyprus started after 9.3 Ma (mid-Tortonian). In NW Cyprus, the reefs moved to a higher structural level on the graben flanks, following extensional subsidence of the depocentre. The timing corresponds to the end of the period of high precipitation and temperature in the Eastern Mediterranean (‘Tortonian wash-house’). (Prista *et al.*, 2015; Böhme *et al.*, 2008; Böhme *et al.*, 2011). The implied transition to a more arid climate resulted in reduced continental run-

662 off and nutrient input, factors which could have helped trigger renewed reef growth (Hallock
663 & Schlager, 1986; Fabricius, 2005).

664 Decreased seawater temperature during the Late Miocene is likely to have influenced the
665 marked reduction in coral diversity compared to the Early Miocene (Zachos *et al.*, 2001,
666 2008; Holbourn *et al.*, 2005; Bosellini & Perrin, 2008). Based on their widespread occurrence
667 in the Mediterranean in different local environmental settings, the *poritid*-dominated
668 assemblages that characterise the Late Miocene reefs were probably relative resistant to
669 environmental stresses such as decreased temperature, nutrients or salinity fluctuations
670 (Pomar *et al.*, 2017). The effective exclusion of other coral taxa, in contrast to the Early
671 Miocene reefs, *could have* favoured the rapid construction of the very large monogeneric
672 poritid reefs (e.g. as in S Spain and Majorca). The Late Miocene z-corals in the
673 Mediterranean had a high frame-building capacity, despite their diversity being very low (i.e.
674 poritid-dominated Koronia Member reefs) (Bosellini & Perrin, 2008; Perrin & Bosellini,
675 2012; Vertino *et al.*, 2014; Pomar *et al.*, 2017). This diversity decrease is believed to relate to
676 a combination of closure of the S. Neotethys-Indian Ocean gateway, the effects of slow
677 northward migration of the Mediterranean region, and continuing global temperature
678 decrease (Bosellini & Perrin, 2008; Vertino *et al.*, 2014). In Cyprus and several other areas
679 (e.g. S Italy, Bosellini *et al.*, 2001; Bosellini *et al.*, 2002 & Majorca, Pomar *et al.*, 1996) the
680 poritid-dominated reefs were able to survive into the Early Messinian, as suggested by our
681 6.1 Ma Sr isotopic age.

682 Late Miocene reef growth was controlled less by environmental factors (e.g. temperature;
683 water purity) than by the presence of a suitable substratum and water depth. Rifting of the
684 Polis graben in NW Cyprus produced topographies and water depths eminently suitable for

patch reef growth. Our dating of reef talus points to reef growth during late Mid-Miocene (Late Serravallian) (*c.* 9.3 Ma) to mid-Late Miocene (Mid-Messinian) (*c.* 6.1 Ma). Uplifted crust also provided suitable substrates for Late Miocene reef growth in the type area of the Koronia Member along the northern margin of the Troodos ophiolite (Follows & Robertson, 1990) and elsewhere, including the source platform of the Happy Valley material, and the southern periphery of the Troodos massif.

During the Messinian, the climate in the Eastern Mediterranean further deteriorated and was influenced by increased aridity across sub-tropical regions (Tzanova *et al.*, 2015; Herbert *et al.* 2016). The uplift of the Himalayan mountain belt, and possible related changes to the South Asian Monsoon, together with the closure of the Paratethys Seaway could have contributed to increased aridity in the Eastern Mediterranean region (Tzanova *et al.*, 2015; Herbert *et al.*, 2016), although the intensity of aridification in this region is uncertain (Polissar *et al.* 2019).

However, such factors, alone are unlikely to explain the final demise of the Koronia Member reef phase. Instead, the main driver was the isolation of the Mediterranean from the Atlantic and the resulting dramatic sea level fall during the Late Messinian (40-50m fall at the Gibraltar Strait *c.* 5.6Ma, Ohneiser *et al.* 2015), including around Cyprus (Hsü *et al.*, 1973; Robertson *et al.*, 1995; Krijgsman *et al.*, 2002; Duggen *et al.*, 2003; Kouwenhoven *et al.*, 2006; Roveri *et al.*, 2014; Manzi *et al.*, 2016; Meilijson *et al.*, 2019). Increased salinity associated with the sea-level fall is inferred to have affected marginal settings first, as in southern Turkey (Flecker *et al.*, 1998), and is likely to have finally terminated the Late Miocene Koronia Member reef development.

707

708 **Conclusions**

709 Benthic foraminiferal facies accumulated on a bathymetric high in the Akamas Peninsula,
710 NW Cyprus, during Late Oligocene (Chattian) (27.8 – 23.0 Ma). The benthic foraminiferal
711 assemblage is similar to shallow-water carbonates of Late Oligocene-Early Miocene age in
712 some other areas of the Mediterranean region. The localised neritic facies in NW Cyprus
713 contrast with continuing pelagic carbonate deposition elsewhere in southern Cyprus.

714 The Early Miocene Terra Member (Pakhna Formation) in NW Cyprus, as in SE Cyprus, was
715 characterised by a diverse coral assemblage, with marginal facies including benthic
716 foraminiferal shoals. The reefs in NW Cyprus are now almost entirely preserved as
717 redeposited talus. Debris was shed from the Early Miocene reefs (along with associated and
718 pre-existing facies) during the Mid-Miocene until *c.* 13.7 Ma (Serravallian). This detritus
719 probably post-dates the reef growth. No one factor appears to have caused Early Miocene
720 reef demise in NW Cyprus and many other areas of the Mediterranean. Controlling factors
721 are likely to have included glacio-eustatic global sea-level/temperature fall, variable
722 siliciclastic/nutrient input, changed current strength/distribution, regional tectonic subsidence,
723 and local tectonic uplift/subsidence.

724 The second-phase, Koronia Member in NW Cyprus reef developed on structurally controlled
725 highs, during rifting of the neotectonic Polis graben. Dating of talus supports major rifting
726 during the Tortonian (*c.* 9.3 Ma) to mid-Messinian) (*c.* 6.1 Ma). Extensional tectonics
727 persisted during the late-Messinian, Pliocene and Recent, based on sedimentary and structural
728 evidence.

729 Reduced sea-water temperature, increased aridity and/or reduced siliciclastic input after the
730 mid-Miocene are likely to have contributed to the nucleation and growth of environmentally

resistant, monogeneric poritid corals during the Tortonian-early Messinian, as supported by new dating.

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References

- Aktaş G. & Robertson A.H.F., 1984. The Maden Complex, SE Turkey: evolution of a Neotethyan active margin. *In*: Dixon J.E. & Robertson A.H.F. (eds) *The Geological Evolution of the Eastern Mediterranean*. Geological Society Special Publication, **17**, 375-402.
- Backman, J. Raffi, I. Rio, D. Fornaciari, E. & Pälike, H., 2012. Biozonation and biochronology of Miocene through Pleistocene calcareous nannofossils from low and middle latitudes. *Newsletters on Stratigraphy*, **45**, 221-244.

- 754 Backman, J. & Shackleton, N.J., 1983. Quantitative biochronology of Pliocene and early
755 Pleistocene calcareous nannofossils from the Atlantic, Indian and Pacific oceans. *Marine*
756 *Micropaleontology*, **8**, 141–170.
- 757 Balmer, E. M. Robertson, A. H. F., Raffi, I. & Kroon, D., 2019. Pliocene–Pleistocene
758 sedimentary development of the syntectonic Polis graben, NW Cyprus: Evidence from facies
759 analysis, nannofossil biochronology and strontium isotope dating. *Geological Magazine*, **156**,
760 889–917.
- 761 Bagnall, P. S., 1960. The Geology and Mineral Resources of the Pano Lefkara-Larnaca area,
762 Cyprus. Geological Survey Department Memoir, **5**, 116 p.
- 763 Banner, F. T., Lord, A. R. & BouDagher-Fadel, M. K., 1999. The Terra Limestones Member
764 (Miocene) of Western Cyprus. *Greifswalder Geowissenschaftliche Beiträge*, **6**, 503-515.
- 765 Bassant, P., Van Buchem, F. S. P., Strasser, A. & Görür, N., 2005. The stratigraphic
766 architecture and evolution of the Burdigalian carbonate-siliciclastic sedimentary systems of
767 the Mut Basin, Turkey. *Sedimentary Geology*, **173**, 187-232.
- 768 Bear, L. M., 1960. The Geology and Mineral Resources of the Akaki-Lythrodondha area,
769 Cyprus. Geological Survey Department Memoir, **3**, 122 p.
- 770 Belkebir, L., Mansour, B., Bessedik, M., Saint-Martin, J.P., Belbarbi, M. & Chaix, C., 1994.
771 Présence d’une construction récifale à Djebel Chott (Dahra occidental, Algérie): témoin du
772 maximum transgressif du Miocène moyen en Méditerranée). *Interim Colloqu. RCMNS*
773 *Marseille, France.(abstract book)*, **4**.
- 774 Benisek M-F., Betzler, C., Marciano, G. & Mutti, M., 2009. Coralline-algal assemblages of
775 Burdigalian platform slope: implications for carbonate platform reconstruction (northern
776 Sardinia, western Mediterranean). *Facies*, **55**, 375-386.
- 777 Betzler, c. & Schmitz, S., 1997. First record of *Borelis melo* and *Dendritina* sp. in the
778 Messinian of SE Spain (Cabo de Gata, Province Almeria). *Palaeontologische Zeitschrift*, **71**,
779 211-216.

780 Bialik, O.M., Frank, M., Betzler, C., Zammit, R. & Waldmann, N.D., 2019. Two-step closure
781 of the Miocene Indian Ocean Gateway to the Mediterranean. *Scientific Reports*, **9**, 8842,
782 <https://doi.org/10.1038/s41598-019-45308-7>.

783 Böhme, M., Ilg, A. & Winklhofer, M., 2008. Late Miocene “washhouse” climate in Europe.
784 *Earth and Planetary Science Letters*, **275**, 393–401.

785 Böhme, M., Winklhofer, M. & Ilg, A., 2011. Miocene precipitation in Europe: Temporal
786 trends and spatial gradients. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **304**, 212–
787 218, <https://doi.org/https://doi.org/10.1016/j.palaeo.2010.09.028>.

788 Bosellini, F. R., 2006. Biotic changes and their control on Oligocene-Miocene reefs: A case
789 study from the Apulia Platform margin (southern Italy). *Palaeogeography,*
790 *Palaeoclimatology, Palaeoecology*, **241**, 393-409.

791 Bosellini A., Russo A., Arush M.A. & Cabdulquar M.M., 1987. The Oligo-Miocene of Eil
792 (NE Somalia): a prograding coral-*Lepidocyclus* system. *Journal of African Earth Sciences*,
793 **6**, 583-593.

794 Bosellini, F.R., Russo, A. & Vescogni, A. 2001. Messinian reef-building assemblages of the
795 Salento Peninsula (southern Italy): palaeobathymetric and palaeoclimatic significance.
796 *Palaeogeography, Palaeoclimatology, Palaeoecology*, **175**, 7–26,
797 [https://doi.org/https://doi.org/10.1016/S0031-0182\(01\)00383-2](https://doi.org/https://doi.org/10.1016/S0031-0182(01)00383-2).

798 Bosellini, F.R., Russo, A. & Vescogni, A., 2002. The Messinian reef complex of the Salento
799 Peninsula (southern Italy): Stratigraphy, facies and paleoenvironmental interpretation. *Facies*,
800 **47**, 91–112.

801 Bosellini, F. & Perrin, C., 1994. The coral fauna of Vitigliano: qualitative and quantitative
802 analysis in a back reef environment (Castro Limestone, Late Oligocene, Salento Peninsula,
803 southern Italy). *Bollettino della Società Paleontologica Italiana*, **33**, 171-181.

804 Bosellini, F. R. & Perrin, C., 2008. Estimating Mediterranean Oligocene–Miocene sea-
805 surface temperatures: an approach based on coral taxonomic richness. *Palaeogeography,*
806 *Palaeoclimatology, Palaeoecology*, **258**, 71-88.

807 Bosence, D., 2005. A genetic classification of carbonate platforms based on their basinal and
808 tectonic settings in the Cenozoic. *Sedimentary Geology*, **175**, 49-72.

809 Bossio, A., Esteban, M., Mazzanti, R., Mazzei, R. & Salvatorini, G., 1996. Rosignano reef
810 complex (Messinian), Livornesi Mountains, Tuscany, Central Italy. Models for Carbonate
811 Stratigraphy from Miocene Reef Complexes of Mediterranean Regions. *In*: Franseen E.K.,
812 Esteban M., Ward W.C. & Rouchy J.M. (eds) Models for Carbonate Stratigraphy, from
813 Miocene Reef Complex of the Mediterranean Area. Concepts in Sedimentology and
814 Paleontology, **5**, Society for Sedimentary Geology, Tulsa, Oklahoma, U.S.A, 277-294.

815 BouDagher-Fadel, M. & Lord, A., 2006. Illusory stratigraphy decoded by Oligocene-
816 Miocene autochthonous and allochthonous foraminifera in the Terra Member, Pakhna
817 Formation (Cyprus). *Stratigraphy*, **3**, 217-226.

818 Brachert, T. C., Betzler, C., Braga, J. c. & Martin, J. M., 1996. Record of climatic change in
819 neritic carbonates: turnover in biogenic associations and depositional modes (Late Miocene,
820 southern Spain). *Geologische Rundschau*, **85**, 327-337.

821 Brachert, T. C., Reuter, M., Kroeger, K. F. & Lough, J. M., 2006. Coral growth bands: a new
822 and easy to use paleothermometer in paleoenvironment analysis and paleoceanography (late
823 Miocene, Greece). *Paleoceanography*, 21(4). <https://doi.org/10.1029/2006PA001288>

824 Braga, J.C., Jimenez, A.P., Martin, J.M. & Rivas, P., 1996. Middle Miocene Coral-Oyster
825 Reefs, Murchas, Granada, Southern Spain, *In*: Franseen E.K., Esteban M., Ward W.C. &
826 Rouchy J.M. (eds) Models for Carbonate Stratigraphy, from Miocene Reef Complex of the
827 Mediterranean Area. *Concepts in Sedimentology and Paleontology*, **5**, Society for
828 Sedimentary Geology, Tulsa, Oklahoma, U.S.A, 131-139.

829 Braga, J. c. & Aguirre, J., 2001. Coralline algal assemblages in upper Neogene reef and
830 temperate carbonates in Southern Spain. *Palaeogeography, Palaeoclimatology,*
831 *Palaeoecology*, **175**, 27-41.

832 Braga, J.C., Vescogni, A., Bosellini, F.R. & Aguirre, J., 2009. Coralline algae (Corallinales,
833 Rhodophyta) in the western and central Mediterranean Messinian reefs. *Palaeogeography*
834 *Palaeoclimatology Palaeoecology*, **275**, 113-128.

- 835 Brandano M., 2003. Tropical/subtropical inner ramp facies in lower Miocene “Calcarei a
836 briozoi e litotamni” of the Monte Lungo area (Cassino Plain, Central Apennines, Italy).
837 *Bollettino Società Geologica Italiana*, **122**, 85-98.
- 838 Brandano, M., Bosellini, F.R., Mazzucchi, A. & Tomassetti, L., 2016. Coral assemblages and
839 bioconstructions adapted to the depositional dynamics of a mixed carbonate-siliciclastic
840 setting: the case study of the Burdigalian Bonifacio Basin (South Corsica), *Rivista Italiana di*
841 *Paleontologia e Stratigrafia*, **122**, 37-52.
- 842 Brandano, M., Cornacchia, I., Raffi, I., Tomassetti, L. & Agostini, S., 2017. The Monterey
843 Event within the Central Mediterranean area: The shallow- water record. *Sedimentology*, **64**,
844 286-310.
- 845 Buchbinder, B. Martinotti, G. M. Siman-Tov, R. & Zilberman, E., 1993. Temporal and
846 spatial relationships in Miocene reef carbonates in Israel. *Palaeogeography*,
847 *Palaeoclimatology, Palaeoecology*, **101**, 97-116.
- 848 Buchbinder, B. & Zilberman, E. 1997. Sequence stratigraphy of Miocene-Pliocene carbonate-
849 siliciclastic shelf deposits in the eastern Mediterranean margin (Israel): effects of eustasy and
850 tectonics. *Sedimentary Geology*, **112**, 7–32.
- 851 Cahuzac, B. & Chaix, C., 1996. Structural and faunal evolution of Chattian–Miocene reefs
852 and corals in western France and the northeastern Atlantic Ocean *In*: Franseen, E. K. Esteban,
853 M. Ward, W. c. & Rouchy, J. (eds) *Models for Carbonate Stratigraphy from Miocene Reef*
854 *Complexes of Mediterranean Regions*, Society of Economic Paleontologists and
855 Mineralogists, Tulsa, Oklahoma, 105-127.
- 856 Cahuzac, B. & Poignant, A., 1997. Essai de biozonation de l’Oligo-Miocène dans les bassins
857 européens à l’aide des grands foraminifères néritiques. *Bulletin de la Société géologique de*
858 *France*, **168**, 155-169.
- 859 Calvet, F., Esteban, M. & Permanyer, A., 1994. Mid Miocene coral reefs in the Gulf of
860 Valencia, NE Spain. *In*: Saint Martin, J.P. Cornee, J.J. (eds) *Miocene Reefs and Carbonate*
861 *Platforms of the Mediterranean. Interim Colloquium RCMNS, Marseille*, 3–6.

862 Cannings, T., 2018. *Microfossil and strontium isotope constraints on the age and*
863 *development of the Miocene-Pliocene Polis graben, North West Cyprus*. Masters thesis
864 (unpublished), University of Edinburgh.

865 Civitelli, G., Brandano, M., 2005. Atlante delle litofacies e modello deposizionale dei Calcarei
866 a Briozoi e Litotamni nella Piattaforma carbonatica laziale-abruzzese. Bollettino Società
867 Geologica Italiana, **124**, 611-643.

868 Chen, G. & Robertson, A. H. F., 2019. Provenance and magmatic-tectonic setting of
869 Campanian-aged volcanoclastic sandstones of the Kannaviou Formation in western Cyprus:
870 Evidence for a South-Neotethyan continental margin volcanic arc. Sedimentary Geology,
871 **388**, 114-138.

872 Cherchi, A., Murru, M. & Simone, L. 2000. Miocene carbonate factories in the syn-rift
873 Sardinia Graben subbasins (Italy). *Facies*, **43**, 223–240, <https://doi.org/10.1007/bf02536992>.

874 Chevalier J.P., 1962. Recherches sur les madréporaires et les formations récifales miocènes
875 de la Méditerranée occidentale. Mémoires de la Société Géologique de France, **93**, 1–558.

876 Cohen, K.M., Harper, D.A.T., Gibbard, P.L., 2020. ICS International Chronostratigraphic
877 Chart, 2020/01. International Commission on Stratigraphy, IUGS. www.stratigraphy.org

878 Coletti, G., Stainbank, S., Fabbrini, A., Spezzaferri, S., Foubert, A., Kroon, D. & Betzler, C.,
879 2018. Biostratigraphy of large benthic foraminifera from Hole U1468A (Maldives): A CT-
880 scan taxonomic approach. *Swiss Journal of Geosciences*, **111**, 523-536.

881 Coletti, G., Basso, D., Betzler, C., Robertson, A.H.F., Bosio, G., El Kateb, A., Foubert, A.,
882 Meilijson, A., Spezzaferri, S., 2019. Environmental evolution and geological significance of
883 the Miocene carbonates of the Eratosthenes Seamount (ODP Leg 160). *Palaeogeography*
884 *Palaeoclimatology Palaeoecology*, **530**, 217-235.

885 Coletti, G. & Basso, D., 2020. Coralline algae as depth indicators in the Miocene carbonates
886 of the Eratosthenes Seamount (ODP Leg 160, Hole 966F). *Geobios*, **60**, 29-46.

887 Constantinou, G., 1995. *100,000 Geological Map of Cyprus*. Geological Survey
888 Department, Nicosia, Cyprus.

889 Danese, E., 1999. Upper Miocene carbonate ramp deposits from the southernmost part of
890 Maiella Mountain (Abruzzo, Central Italy). *Facies*, **41**, 41–54.

891 De Vleeschouwer, D., Vahlenkamp, M., Crucifix, M. & Pälike, H., 2017. Alternating
892 Southern and Northern Hemisphere climate response to astronomical forcing during the past
893 35 m.y. *Geology*, **45**, 375–378.

894 Duggen, S., Hoernle, K., Van den Bogaard, P., Rüpke, L. & Morgan, J. P., 2003. Deep roots
895 of the Messinian salinity crisis. *Nature*, **422** (6932), 602–606.

896 Eaton, S. & Robertson, A. H. F., 1993. The Miocene Pakhna Formation, southern Cyprus and
897 its relationship to the Neogene tectonic evolution of the Eastern Mediterranean. *Sedimentary*
898 *Geology*, **86**, 273–296.

899 Elion, P., 1983. Etude structural et sédimentologique du bassin Neogène de Pissouri
900 (Chypre). Thèse 3^e cycle, Université de Paris Sud, Orsay, France.

901 Emeis K.C., Robertson A.H.F., Richter C., *et al.*, 1996. Proceedings of the Ocean Drilling
902 Program, Initial Reports, **160**, Ocean Drilling Program, College Station, Texas, U.S.A, 972p.

903 Esteban, M., 1979. Significance of the upper Miocene coral reefs of the western
904 Mediterranean. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **29**, 169–188.

905 Esteban, M., 1996. An overview of Miocene reefs from Mediterranean areas: general trends
906 and facies models. In: Franseen, E. K. Esteban, M. Ward, W. c. & Rouchy, J. (eds) *Models*
907 *for Carbonate Stratigraphy from Miocene Reef Complexes of Mediterranean Regions*,
908 Society of Economic Paleontologists and Mineralogists, Tulsa, Oklahoma, 3–53.

909 Fabricius, K.E. 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs:
910 review and synthesis. *Marine Pollution Bulletin*, **50**, 125–146,
911 <https://doi.org/https://doi.org/10.1016/j.marpolbul.2004.11.028>.

912 Flecker, R., Robertson, A.H.F., Poisson, A. & Muller, C., 1995. Facies and tectonic
913 significance of two contrasting Miocene Basins in south coastal Turkey. *Terra Nova*, **7**, 221–
914 232.

915 Flecker, R., Ellam, R.M., Müller, C., Poisson, A., Robertson, A.H.F. & Turner, J., 1998.
916 Application of Sr isotope stratigraphy and sedimentary analysis to the origin and evolution of

917 the Neogene Basins in the Isparta Angle, southern Turkey. *Tectonophysics*, **298**, 83–101.

918 Flecker, R., Poisson, A. & Robertson, A.H.F., 2005. Facies and palaeogeographic evidence
 919 for the Miocene evolution of the Isparta Angle in its regional eastern Mediterranean context.
 920 *Sedimentary Geology*, **173**, 277–314.

921 Flower, B. P. & Kennett, J. P., 1994. The middle Miocene climatic transition: East Antarctic
 922 ice sheet development, deep ocean circulation and global carbon cycling. *Palaeogeography*,
 923 *Palaeoclimatology*, *Palaeoecology*, **108**, 537-555.

924 Follows, E. J., 1992. Patterns of reef sedimentation and diagenesis in the Miocene of
 925 Cyprus. *Sedimentary Geology*, **79**, 225-253.

926 Follows, E. J. & Robertson, A. H. F., 1990. Sedimentology and structural setting of Miocene
 927 reefal limestones in Cyprus. In: Panayiotou A. (ed) *Ophiolites: Oceanic Crustal Analogues*.
 928 Geological Survey Department, Nicosia, Cyprus, 207-216.

929 Follows, E. J. Robertson, A. H. F. & Scoffin, T. P., 1996. Tectonic controls on Miocene reefs
 930 and related carbonate facies in Cyprus. In: Franseen, E. K. Esteban, M. Ward, W. c. &
 931 Rouchy, J. (eds) *Models for Carbonate Stratigraphy from Miocene Reef Complexes of*
 932 *Mediterranean Regions*, Society of Economic Paleontologists and Mineralogists, Tulsa,
 933 Oklahoma, 295-315.

934 Franseen E.K., Esteban M., Ward, W.C., Rouchy, G.M., 1996. Models for carbonate
 935 stratigraphy from Miocene reef complexes of Mediterranean regions: introduction. In:
 936 Franseen, E. K. Esteban, M. Ward, W. c. & Rouchy, J. (eds) *Models for Carbonate*
 937 *Stratigraphy from Miocene Reef Complexes of Mediterranean Regions*, Society of Economic
 938 Paleontologists and Mineralogists, Tulsa, Oklahoma, V-IX.

939 Galloni, F., Cornee, J. J., Rebelle, M. & Ferrandini, M. (2001). Sedimentary anatomy of early
 940 Miocene coral reefs in South Corsica (France) and South Sardinia (Italy). *Géologie*
 941 *méditerranéenne*, **28**, 73-77.

942 Gass, I. G., 1960. The Geology and Mineral resources of the Dhali Area: Geological Survey
 943 Department Memoir, **4**.

- 944 Gass, I. G., Masson-Smith, E. M., 1963. The geology and gravity anomalies of the Troodos
945 massif, Cyprus. Royal Society of London, Philosophical Transactions, Series A, **255**, 417-
946 467.
- 947 Grasso, M. & Pedley, H.M., 1985. The Pelagian Islands: a new geological interpretation from
948 sedimentological and tectonic studies and its bearing on the evolution of the Central
949 Mediterranean Sea (Pelagian Block). *Geologica Romana*, **24**, 13–34.
- 950 Gurbuz, K., 1999. Regional implications of structural and eustatic Controls in the evolution
951 of submarine fans: an example from the Miocene Adana Basin, Southern Turkey. *Geological*
952 *Magazine*, **136**, 311 – 319.
- 953 Gurbuz, M.O., 2015. Tectonic and sea level controls on the back-stepping early Miocene
954 carbonate platforms: Adana Basin, Turkey. Masters thesis (unpublished), The University of
955 Texas.
- 956 Hallock, P. & Schlager, W. 1986. Nutrient excess and the demise of coral reefs and carbonate
957 platforms. *Palaios*, **1**, 389–398, <https://doi.org/10.2307/3514476>.
- 958 Hardenberg, M. F. & Robertson, A. H. F., 2007. Sedimentology of the NW margin of the
959 Arabian plate and the SW–NE-trending Nahr El-Kabir half-graben in northern Syria during
960 the latest Cretaceous and Cenozoic. *Sedimentary Geology*, **201**, 231–266.
- 961 Hayward, A. B., Robertson, A. H. F. & Scoffin, T. P., 1996. Miocene patch reefs from a
962 Mediterranean marginal terrigenous setting in southwest Turkey. In: Franseen, E.K., Esteban
963 M., Ward W.C. & Rouchy J.M. (eds) Models for Carbonate Stratigraphy from Miocene Reef
964 complexes of the Mediterranean area. *Concepts in Sedimentology and Paleontology*, **5**,
965 Society for Sedimentary Geology, Tulsa, Oklahoma, U.S.A, 317-332.
- 966 Henderiks, J. & Törner, A., 2006. Reproducibility of coccolith morphometry: Evaluation of
967 spraying and smear slide preparation techniques. *Marine Micropaleontology*, **58**, 207–218.
- 968 Henson, F. R. S. Browne, R. V. & McGinty, J., 1949. A synopsis of the stratigraphy and
969 geological history of Cyprus. *Quarterly Journal of the Geological Society*, **105**, 1-41.

970 Herold, N., Huber, M., Müller, R. D. & Seton, M., 2012. Modeling the Miocene climatic
 971 optimum: Ocean circulation. *Palaeoceanography and Palaeoclimatology*, **27**,
 972 doi:10.1029/2010PA002041

973 Herbert, T.D., Lawrence, K.T., Tzanova, A., Peterson, L.C., Caballero-Gill, R. & Kelly, C.S.
 974 2016. Late Miocene global cooling and the rise of modern ecosystems. *Nature Geoscience*, **9**,
 975 843–847, <https://doi.org/10.1038/ngeo2813>.

976 Hladil, J., Otava, J. & Galle, A., 1991. Oligocene carbonate buildups of the Sirt Basin, Libya.
 977 In: M.J. Salem, O.S. Hammuda, B.A. Eliagoubi (eds), *The Geology of Libya*, Symposium on
 978 the Geology of Libya, Elsevier, Amsterdam, **4**, 1401-1420.

979 Holbourn, A., Kuhnt, W., Schulz, M. & Erlenkeuser, H., 2005. Impacts of orbital forcing and
 980 atmospheric carbon dioxide on Miocene ice-sheet expansion. *Nature*, **438**(7067), 483-487.

981 Holbourn, A. E., Kuhnt, W., Clemens, S. C., Kochhann, K. G., Jöhnck, J., Lübbers, J. &
 982 Andersen, N., 2018. Late Miocene climate cooling and intensification of southeast Asian
 983 winter monsoon. *Nature communications*, **9**, 1-13.

984 Hsü, K. J., Ryan, W. B. & Cita, M. B., 1973. Late Miocene desiccation of the Mediterranean.
 985 *Nature*, **242** (5395), 240-244.

986 Hüsing, S. K. Zachariasse, W. J. Van Hinsbergen, D. J. Krijgsman, W. Inceöz, M.
 987 Harzhauser, M. & Kroh, A., 2009. Oligocene–Miocene basin evolution in SE Anatolia,
 988 Turkey: constraints on the closure of the eastern Tethys gateway. In: Van Hinsbergen, D. J. J.
 989 Edwards, M. A. Govers, R. (eds) *Collision and Collapse at the Africa-Arabia-Eurasia*
 990 *Subduction Zone, Geological Society, London, Special Publications*, **311**, 107-132.

991 Iaccarino, S., Castradori, D., Cita, M. B., Di Stefano, E., Gaboardi, S., McKenzie, J. A. &
 992 Sprovieri, R., 1999. The Miocene/Pliocene boundary and the significance of the earliest
 993 Pliocene flooding in the Mediterranean. *Memoire Società Geologica Italiana*, **54**, 109-131.

994 Iaccarino, S. M. Di Stefano, A. Foresi, L. M. Turco, E. Baldassini, N. Cascella, A. & Lirer,
 995 F., 2011. High-resolution integrated stratigraphy of the upper Burdigalian-lower Langhian in
 996 the Mediterranean: the Langhian historical stratotype and new candidate sections for defining
 997 its GSSP. *Stratigraphy*, **8**, 199-215.

- 998 Janson, X. Van Buchem, F. S. P. Dromart, G. Eichenseer, H. T. Dellamonica, X. Boichard, R.
 999 & Eberli, G., 2010. Architecture and facies differentiation within a Middle Miocene
 1000 carbonate platform, Ermenek, Mut Basin, southern Turkey. *In*: Van Buchem, F. S. P. Gerdes,
 1001 K. D. Esteban, M. (eds) *Mesozoic and Cenozoic Carbonate Systems of the Mediterranean*
 1002 *and the Middle East: Stratigraphic and Diagenetic Reference Models. Geological Society,*
 1003 *London, Special Publications, 329, 265-290.*
- 1004 John, C.M., Karner, G.D., Browning, E., Leckie, R.M., Mateo, Z., Carson, B. & Lowery, C.,
 1005 2011. Timing and magnitude of Miocene eustasy derived from the mixed siliciclastic-
 1006 carbonate stratigraphic record of the northeastern Australian margin. *Earth and Planetary*
 1007 *Science Letters, 304, 455–467.*
- 1008 Kennett, J.P., Houtz, R.E., Shackleton, N.J. & Kennett, J.P., 1975. Paleotemperature History
 1009 of the Cenozoic and the Initiation of Antarctic Glaciation: Oxygen and Carbon Isotope
 1010 Analyses in DSDP Sites 277, 279 and 281. *In*: Kennett, J.P., Houtz, R.E., Shackleton, N.J. &
 1011 Kennett, J.P. (eds) *Initial Reports of the Deep Sea Drilling Project*, U. S. Government
 1012 Printing Office, **29**, 743–756.
- 1013 Kempler, D., 1998. Eratosthenes Seamount: The Possible Spearhead of Incipient Continental
 1014 Collision in the eastern Mediterranean. *In*: Robertson, A. H. F., Emeis, K.C., Richter, C. &
 1015 Camerlenghi, A. (eds) *Proceedings of the Ocean Drilling Program, Scientific Results, 160,*
 1016 *Ocean Drilling Program, College Station, TX, 709-721.*
- 1017 Kiessling, W., 2009. Geologic and biologic controls on the evolution of reefs. *Annual Review*
 1018 *of Ecology, Evolution, and Systematics, 40, 173-192.*
- 1019 Kinnaird, T. C., Robertson, A. H. F. & Morris, A., 2011. Timing of uplift of the Troodos
 1020 Massif (Cyprus) constrained by sedimentary and magnetic polarity evidence. *Journal of the*
 1021 *Geological Society, 168, 457-470.*
- 1022 Kinnaird, T. c. & Robertson, A. H. F., 2013. Tectonic and sedimentary response to incipient
 1023 diachronous collision of the African and Eurasian plates in southern Cyprus, easternmost
 1024 Mediterranean region. *In*: Robertson, A. H. F. Parlak, O. Ünlügenç, U. c. (eds) *Geological*
 1025 *Development of Anatolia and the Easternmost Mediterranean Region. Geological Society,*
 1026 *London, Special Publications, 372, 585-614.*

1027 Kleypas, J. A. Buddemeier, R. W. & Gattuso, J. P., 2001. The future of coral reefs in an age
1028 of global change. *International Journal of Earth Sciences*, **90**, 426-437.

1029 Kouwenhoven, T.J., Morigi, C., Negri, A., Giunta, S., Krijgsman, W. & Rouchy, J.M., 2006.
1030 Paleoenvironmental evolution of the eastern Mediterranean during the Messinian: Constraints
1031 from integrated microfossil data of the Pissouri Basin (Cyprus). *Marine Micropaleontology*,
1032 **60**, 17–44.

1033 Krijgsman W., Blanc-Valleron M. M., Flecker R., Hilgen F. J., Kouwenhoven T. J., Orszag-
1034 Sperber F., Rouchy J. M., 2002. The onset of the Messinian salinity crisis in the Eastern
1035 Mediterranean (Pissouri Basin, Cyprus). *Earth and Planetary Science Letters*, **194**, 299–310.

1036 Lirer, F., Foresi, L. M., Iaccarino, S. M., Salvatorini, G., Turco, E., Cosentino, C., Sierro, F.
1037 J. & Caruso, A., 2019. Mediterranean Neogene planktonic foraminifer biozonation and
1038 biochronology. *Earth-Science Reviews*, **196**, 102869.

1039 Lokier, S. W., Wilson, M. E., & Burton, L. M. (2009). Marine biota response to clastic
1040 sediment influx: a quantitative approach. *Palaeogeography, Palaeoclimatology,*
1041 *Palaeoecology*, **281**, 25-42.

1042 Lord, A.R., Panayides, I., Urquhart, E., Xenophontos, c. & Malpas, J., 2000. A
1043 biochronostratigraphical framework for the Late Cretaceous–Recent circum-Troodos
1044 sedimentary sequence, Cyprus. *In: Proceedings of the Third International Conference on the*
1045 *Geology of the Eastern Mediterranean*. Geological Survey Department, Nicosia. **297**, 289-
1046 297.

1047 Mankiewicz, C., 1996. The Middle to Upper Miocene carbonate complex of Nijar, Almeria
1048 Province. *In: Franseen, E. K. Esteban, M. Ward, W. c. & Rouchy, J. (eds) Models for*
1049 *Carbonate Stratigraphy from Miocene Reef Complexes of Mediterranean Regions*, Society of
1050 Economic Paleontologists and Mineralogists, Tulsa, Oklahoma, 141-157.

1051 Manzi, V., Lugli, S., Roveri, M., Dela Pierre, F., Gennari, R., Lozar, F., Natalicchio, M.,
1052 Schreiber, B.C., Taviani, M., and Turco, E., 2016. The Messinian salinity crisis in Cyprus: a
1053 further step towards a new stratigraphic framework for Eastern Mediterranean. *Basin*
1054 *Research*, **28**, 207–236.

1055 Matteucci R. & Schiavinotto F., 1977. Studio biometrico di *Nephrolepidina*, *Eulepidina* e
1056 *Cycloclypeus* in due campioni dell'Oligocene di Monte la Rocca, L'Aquila (Italia Centrale).
1057 *Geologica Romana*, **16**, 141-171.

1058 McArthur, J. M. Howarth, R. J. & Bailey, T. R., 2001. Strontium isotope stratigraphy:
1059 LOWESS version 3: best fit to the marine Sr-isotope curve for 0–509 Ma and accompanying
1060 look-up table for deriving numerical age. *Journal of Geology*, **109**, 155-170.

1061 McArthur, J. M. & Howarth, R. J., 2004. Sr-isotope stratigraphy. *In*: Gradstein, F.M. Ogg,
1062 J.G. and Smith, A.G. (eds) A Geological Timescale, 2004, *Cambridge University Press*,
1063 *Cambridge* 589

1064 McCay, G.A., Robertson, A.H.F., Kroon, D., Raffi, I., Ellam, R.M. & Necdet, M. 2013.
1065 Stratigraphy of Cretaceous to Lower Pliocene sediments in the northern part of Cyprus based
1066 on comparative $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic, nannofossil and planktonic foraminiferal dating.
1067 *Geological Magazine*, **150**, 333–359, <https://doi.org/10.1017/S0016756812000465>.

1068 Meilijson, A., Hilgen, F., Sepúlveda, J., Steinberg, J., Fairbank, V., Flecker, R., Waldmann,
1069 N.D., Spaulding, S.A., Bialik, O.M. & Boudinot, F.G., 2019. Chronology with a pinch of
1070 salt: Integrated stratigraphy of Messinian evaporites in the deep Eastern Mediterranean
1071 reveals long-lasting halite deposition during Atlantic connectivity. *Earth-Science Reviews*,
1072 **194**, 374–398.

1073 Miller, K. G., Kominz, M. A., Browning, J. V., Wright, J. D., Mountain, G. S., Katz, M. E. &
1074 Pekar, S. F., 2005. The Phanerozoic record of global sea-level change. *Science*, **310**(5752),
1075 1293-1298.

1076 Miller, K.G., Browning, J. V., John Schmelz, W., Kopp, R.E., Mountain, G.S. & Wright,
1077 J.D., 2020. Cenozoic sea-level and cryospheric evolution from deep-sea geochemical and
1078 continental margin records. *Science Advances*, **6**, <https://doi.org/10.1126/sciadv.aaz1346>.

1079 Morel, S. W., 1960. The Geology and Mineral Resources of the Apsiou-Akrotiri area, Cyprus
1080 Geological Survey Department Memoir, **7**, 51-88.

1081 Mutti, M., Bernoulli, D. & Stille, P., 1997 Temperate carbonate platform drowning linked to
1082 Miocene oceanographic events: Maiella platform margin, Italy. *Terra Nova*, **9**, 199-125.

1083 NASA/METI/AIST/Japan Spacesystems, and U.S./Japan ASTER Science Team., 2019.
 1084 ASTER Global Digital Elevation Model V003 Data set]. NASA EOSDIS Land Processes
 1085 DAAC. <https://doi.org/10.5067/ASTER/ASTGTM.003>

1086 Ohneiser, C., Florindo, F., Stocchi, P., Roberts, A.P., DeConto, R.M. & Pollard, D., 2015.
 1087 Antarctic glacio-eustatic contributions to late Miocene Mediterranean desiccation and
 1088 reflooding. *Nature Communications*, **6**, 8765, <https://doi.org/10.1038/ncomms9765>.

1089 Oosterbaan, A.F.F., 1988. Early Miocene corals from the Aquitaine Basin (SW France).
 1090 *Mededelingen van de Werkgroep voor Tertiaire en Kwartaire Geologie*, **25**, 247-284.

1091 Oosterbaan, A.F.F., 1990. Notes on a collection of Badenian (Middle Miocene) corals from
 1092 Hungary in the National Museum of Natural History at Leiden (the Netherlands).
 1093 *Mededelingen van de Werkgroep voor Tertiaire en Kwartaire Geologie*, **27**, 3–15.

1094 Orszag-Sperber, F., Rouchy, J.M. & Elion, P., 1989. The sedimentary expression of regional
 1095 tectonic events during the Miocene-Pliocene transition in the southern Cyprus basins.
 1096 *Geological Magazine*, **126**, 291–299.

1097 Orszag-Sperber, F., Caruso, A., Blanc-Valleron, M.M., Merle, D. & Rouchy, J.M., 2009. The
 1098 onset of the Messinian salinity crisis: Insights from Cyprus sections. *Sedimentary Geology*,
 1099 **217**, 52–64.

1100 Özcan, E. & Less, G., 2009. First record of the co-occurrence of western Tethyan and Indo-
 1101 Pacific larger foraminifera in the Burdigalian of the Mediterranean province. *The Journal of*
 1102 *Foraminiferal Research*, **39**, 23-39.

1103 Özcan, E., Less, G., Báldi-Beke, M., Kollányi, K. & Acar, F., 2009. Oligo-Miocene
 1104 foraminiferal record (Miogypsinidae, Lepidocyclinidae and Nummulitidae) from the Western
 1105 Taurides (SW Turkey): biometry and implications for the regional geology. *Journal of Asian*
 1106 *Earth Sciences*, **34**, 740-760.

1107 Özcan, E., Less, G., Okay, A. I., Baldi-Beke, M., Kollányi, K., & Yilmaz, İ. Ö., 2010.
 1108 Stratigraphy and larger foraminifera of the Eocene shallow-marine and olistostromal units of
 1109 the southern part of the Thrace Basin, NW Turkey. *Turkish Journal of Earth Sciences*, **19**,
 1110 27-77.

- 1111 Palamakumbura, R.N., Robertson, A.H.F., Kinnaird, T.C., van Calsteren, P., Kroon, D. &
1112 Tait, J.A., 2016. Quantitative dating of Pleistocene deposits of the Kyrenia range, Northern
1113 Cyprus: Implications for timing, rates of uplift and driving mechanisms. *Journal of the*
1114 *Geological Society*, **173**, 933–948.
- 1115 Papadimitriou, N., Deschamps, R., Symeou, V., Souque, C., Gorini, C., Nader, F.H. &
1116 Blanpied, C., 2018. The tectonostratigraphic evolution of Cenozoic basins of the Northern
1117 Tethys: The Northern margin of the Levant Basin. *Oil and Gas Science and Technology*, **73**,
1118 (77), <https://doi.org/10.2516/ogst/2018085>.
- 1119 Payne, A. S. & Robertson, A. H. F., 1995. Neogene supra-subduction zone extension in the
1120 Polis graben system, west Cyprus. *Journal of the Geological Society*, **152**, 613-628.
- 1121 Payne, A. S. & Robertson, A. H. F., 2000. Structural evolution and regional significance of
1122 the Polis graben system, western Cyprus. In: Panayiotou A. (ed) *Proceedings of the Third*
1123 *International Conference on the Geology of the Eastern Mediterranean*, Geological Survey
1124 Department, Nicosia, Cyprus, 45-59.
- 1125 Pearce, J.A. & Robinson, P.T., 2010. The Troodos ophiolitic complex probably formed in a
1126 subduction initiation, slab edge setting. *Gondwana Research*, **18**, 60–81.
- 1127 Pedley, H. M., 1979. Miocene bioherms and associated structures in the Upper Coralline
1128 limestone of the Maltese Islands: their lithification and palaeoenvironment. *Sedimentology*,
1129 **26**, 577-591.
- 1130 Pedley, H. & Grasso, M. 1994. A model for the late Miocene reef-Tripolaceous associations
1131 of Sicily and its relevance to aberrant coral growth-forms and reduced biological diversity
1132 within the Palaeomediterranean. *Geologie Mediterraneenne*, **21**, 109–121,
1133 <https://doi.org/10.3406/geolm.1994.1501>.
- 1134 Perrin c. & Bosellini F., 2012. Paleobiogeography of scleractinian reef corals: Changing
1135 patterns during the Oligocene–Miocene climatic transition in the Mediterranean. *Earth-*
1136 *Science Reviews*, **111**, 1-24.
- 1137 Riegel, B. & Piller, W.E., 2000. Biostromal Coral Facies—A Miocene Example from the
1138 Leitha Limestone (Austria) and its Actualistic Interpretation. *PALAIOS*, **15**, 399–413.

1139 Polissar, P.J., Rose, C., Uno, K.T., Phelps, S.R. & deMenocal, P. 2019. Synchronous rise of
 1140 African C4 ecosystems 10 million years ago in the absence of aridification. *Nature*
 1141 *Geoscience*, 12, 657–660, <https://doi.org/10.1038/s41561-019-0399-2>.

1142 Pomar, L. Ward, W. c. & Green, D. G., 1996. Upper Miocene reef complex of the Lluçmajor
 1143 area, Mallorca, Spain. *In*: Franseen, E.K., Esteban M., Ward W.C.& Rouchy J.M. (eds)
 1144 *Models for Carbonate Stratigraphy from Miocene Reef complexes of the Mediterranean area.*
 1145 *Concepts in Sedimentology and Paleontology*, **5**, Society for Sedimentary Geology, Tulsa,
 1146 Oklahoma, U.S.A, **5**, **191**–225.

1147 Pomar, L., Bassant, P., Brandano, M., Ruchonnet, C., & Janson, X., 2012. Impact of
 1148 carbonate producing biota on platform architecture: insights from Miocene examples of the
 1149 Mediterranean region. *Earth-Science Reviews*, **113**, 186-211.

1150 Pomar, L., Mateu-Vicens, G., Morsilli, M. & Brandano, M., 2014. Carbonate ramp evolution
 1151 during the late Oligocene (Chattian), Salento Peninsula, southern Italy. *Palaeogeography*,
 1152 *Palaeoclimatology*, *Palaeoecology*, **404**, 109-132.

1153 Pomar, L., Baceta, J.I., Hallock, P., Mateu-Vicens, G., Basso, D., 2017. Reef building and
 1154 carbonate production modes in the west-central Tethys during the Cenozoic. *Marine and*
 1155 *Petroleum Geology*, **83**, 261-304.

1156 Prista, G. A., Agostinho, R. J. & Cachão, M. A., 2015. Observing the past to better
 1157 understand the future: a synthesis of the Neogene climate in Europe and its perspectives on
 1158 present climate change. *Open Geosciences*, 1 (open-issue). [https://doi.org/10.1515/geo-2015-](https://doi.org/10.1515/geo-2015-0007)
 1159 0007

1160 Reinhold, C., 1995. Guild structure and aggradation pattern of Messinian Porites patch reefs:
 1161 ecological succession and external environmental control (San Miguel de Salinas Basin, SE
 1162 Spain). *Sedimentary Geology*, **97**, 157–175.

1163 Robertson, A. H. F., 1977a. Tertiary uplift history of the Troodos massif, Cyprus. *Geological*
 1164 *Society of America Bulletin*, **88**, 1763-1772.

1165 Robertson, A. H. F., 1977b. The Kannaviou Formation, Cyprus: volcanoclastic sedimentation
 1166 of a probable late Cretaceous volcanic arc. *Journal of the Geological Society*, **134**, 269-292.

1167 Robertson, A.H.F., 1990. Tectonic evolution of Cyprus. *In*: J. Malpas, E.M. Moores, A.
1168 Panayiotou, c. Xenophontos (eds.), *Ophiolites Oceanic Crustal Analogues*, Proc. Symp.
1169 'Troodos 1987', Geological Survey Department, Cyprus. 235-252.

1170 Robertson, A. H., 1998a. Tectonic significance of the Eratosthenes Seamount: a continental
1171 fragment in the process of collision with a subduction zone in the eastern Mediterranean
1172 (Ocean Drilling Program Leg 160). *Tectonophysics*, **298**, 63-82.

1173 Robertson A.H.F., 1998b. Miocene shallow-water carbonates on the Eratosthenes Seamount,
1174 easternmost Mediterranean Sea. *In*: Robertson, A.H.F., Emeis, K.C., Richter, C.,
1175 Camerlenghi, A. (eds) *Proceedings of the Ocean Drilling Program, Scientific Results*, **160**,
1176 419-436.

1177 Robertson, A. H. F., Boulton, S.J., Tash, K., Yıldırım, N., İnan, N., Yıldız, A. & Parlak, O.,
1178 2016. Late Cretaceous–Miocene sedimentary development of the Arabian continental margin
1179 in SE Turkey (Adıyaman region): Implications for regional palaeogeography and the closure
1180 history of Southern Neotethys. *Journal of Asian Earth Sciences*, **115**, 571–616.

1181 Robertson, A. H. F., Parlak, O. & Ustaömer, T., 2012. Overview of the Palaeozoic–Neogene
1182 evolution of Neotethys in the Eastern Mediterranean region (southern Turkey, Cyprus, Syria).
1183 *Petroleum Geoscience*, **18**, 381-404.

1184 Robertson, A. H. F., Eaton, S., Follows, E. J. & McCallum, J. E., 1991. The role of local
1185 tectonics versus global sea-level changes in the Neogene evolution of the Cyprus active
1186 margin. *In*: Macdonald, D.I.M. (ed) *Sedimentation, Tectonics and Eustasy: Sea-level*
1187 *Changes at Active Margins*, Special Publication of the International Association of
1188 Sedimentologists, **12**, 331-369.

1189 Robertson, A.H.F., Eaton, S., Follows, E.J. & Payne, A.S. 1995. Depositional processes and
1190 basin analysis of Messinian evaporites in Cyprus. *Terra Nova*, **7**, 233–253.

1191 Robertson, A.H.F & Xenophontos, c. 1993. Development of concepts concerning the
1192 Troodos ophiolite and adjacent units in Cyprus. *Geological Society, London, Special*
1193 *Publications*, **76**, 85–119.

1194 Rögl F., 1999. Mediterranean and Paratethys facts and hypotheses of an Oligocene to
1195 Miocene paleogeography (short overview). *Geologica Carpathica*, **50**, 339-349.

- 1196 Rouchy, J.-M., Saint Martin, J.-P., Maurin, A. & Bernet-Rollande, M.-C., 1986. Evolution et
1197 antagonisme des communautés bioconstructrices animales et végétales à la fin du Miocène en
1198 Méditerranée occidentale: biologie et sédimentologie. *Bulletin du Centre de Recherche*
1199 *Exploration et Production Elf Aquitaine*, **10**, 333–348.
- 1200 Roveri, M., Flecker, R., Krijgsman, W., Lofi, J., Lugli, S., Manzi, V., Sierro, F. J., Bertini,
1201 A., Camerlenghi, A., De Lange, G., Govers, R., Hilgen, J. J., Hübscher, C., Meijer, P. Th.,
1202 Stoica, M., 2014. The Messinian Salinity Crisis: Past and future of a great challenge for
1203 marine sciences. *Marine Geology*, **352**, 25–58.
- 1204 Saint-Martin, J. P., & Rouchy, J. M., 1990. Les plateformes carbonatées messiniennes en
1205 Méditerranée occidentale; leur importance pour la reconstitution des variations du niveau
1206 marin au Miocene terminal. *Bulletin de la Société géologique de France*, 6(1), 83-94.
- 1207 Şafak, U., Kelling, G., Gökçen, N.S. & Gürbüz, K., 2005. The mid- Cenozoic succession and
1208 evolution of the Mut basin, southern Turkey, and its regional significance. *Sedimentary*
1209 *Geology*, **173**, 121–150.
- 1210 Schlager, W., 1994. Highstand shedding of carbonate platforms, *Journal of Sedimentary*
1211 *Research*, **64**, 270-281.
- 1212 Schlager, W., 1999. Scaling of sedimentation rates and drowning of reefs and carbonate
1213 platforms, *Geology*, **27**, 183-186.
- 1214 Schuster, F. 2002a. Oligocene and Miocene examples of Acropora-dominated
1215 palaeoenvironments: Mesohellenic Basin (NW Greece) and northern Gulf of Suez (Egypt).
1216 *Proceedings of the 9th International Coral Reefs Symposium*, Bali, Indonesia, **1**, 199–204.
- 1217 Schuster, F. 2002b. Early Miocene corals and associated sediments of the northwestern Gulf
1218 of Suez, Egypt. *Courier Forschungsinst. Senckenberg*, **239**, 57–81.
- 1219 Spezzaferri, S., Cita, M. B. & McKenzie, J. A., 1998. The Miocene/Pliocene boundary in the
1220 Eastern Mediterranean: results from Sites 967 and 969. *In*: Robertson, A. H. F. Emeis, K. c.
1221 Richter, c. Camerlenghi, A. (eds) *Proceedings, Ocean Drilling Program Scientific Results*,
1222 **160**, 9-28, National Science Foundation.

- 1223 Spezzaferri S. & Tamburini F., 2007. Paleodepth variations on the Eratosthenes Seamount
1224 (Eastern Mediterranean): sea level changes or subsidence? *Earth Discussions*, **2**, 115-132.
- 1225 Swarbrick, R. E. & Naylor, M. A., 1980. The Kathikas Melange, SW Cyprus: late Cretaceous
1226 submarine debris flows. *Sedimentology*, **27**, 63-78.
- 1227 Taylforth J.E., McCay G.A., Ellam R., Raffi I., Kroon D., Robertson A.H.F., 2014. Middle
1228 Miocene (Langhian) sapropel formation in the easternmost Mediterranean deep-water basin:
1229 Evidence from northern Cyprus. *Marine and Petroleum Geology*, **57**, 521-536.
- 1230 Tomassetti, L., Bosellini, F.R., Brandano, M., 2013. Growth and demise of a Burdigalian
1231 coral bioconstruction on a granite rocky substrate (Bonifacio Basin, south-eastern Corsica).
1232 *Facies*, **59**, 703-716.
- 1233 Toomey, M., Ashton, A.D. & Perron, J.T., 2013. Profiles of ocean island coral reefs
1234 controlled by sea-level history and carbonate accumulation rates. *Geology*, **41**, 731-734.
- 1235 Toscano, M.A. & Macintyre, I.G., 2003. Corrected western Atlantic sea-level curve for the
1236 last 11,000 years based on calibrated 14C dates from *Acropora palmata* framework and
1237 intertidal mangrove peat. *Coral Reefs*, **22**, 257-270.
- 1238 Tzanova, A., Herbert, T. D., & Peterson, L. (2015). Cooling Mediterranean Sea surface
1239 temperatures during the Late Miocene provide a climate context for evolutionary transitions
1240 in Africa and Eurasia. *Earth and Planetary Science Letters*, **419**, 71-80.
1241 <https://doi.org/https://doi.org/10.1016/j.epsl.2015.03.016>
- 1242 Vertino, A., Stolarski, J., Bosellini, F.R. & Taviani, M., 2014. Mediterranean Corals Through
1243 Time: From Miocene to Present. In: Goffredo, S. & Dubinsky, Z. (eds) *The Mediterranean*
1244 *Sea: Its History and Present Challenges*. Dordrecht, Springer Netherlands, 257-274.
- 1245 Vescogni, A., Bosellini, F. R., Reuter, M. & Brachert, T. C., 2008. Vermetid reefs and their
1246 use as palaeobathymetric markers: New insights from the Late Miocene of the Mediterranean
1247 (Southern Italy, Crete). *Palaeogeography, Palaeoclimatology, Palaeoecology*, **267**, 89-101.
- 1248 Vescogni, A., Bosellini, F. R., Cipriani, A., Gürlér, G., Ilgar, A. & Paganelli, E., 2014. The
1249 Dağpazarı carbonate platform (Mut Basin, Southern Turkey): Facies and environmental

- 1250 reconstruction of a coral reef system during the Middle Miocene Climatic Optimum.
 1251 *Palaeogeography, Palaeoclimatology, Palaeoecology*, **410**, 213-232.
- 1252 Wade, B. S. Pearson, P. N. Berggren, W. A. & Pälike, H., 2011. Review and revision of
 1253 Cenozoic tropical planktonic foraminiferal biostratigraphy and calibration to the geomagnetic
 1254 polarity and astronomical time scale. *Earth-Science Reviews*, **104**, 111-142.
- 1255 Westerhold, T., Bickert, T. & Röhl, U., 2005. Middle to late Miocene oxygen isotope
 1256 stratigraphy of ODP site 1085 (SE Atlantic): New constraints on Miocene climate variability
 1257 and sea-level fluctuations. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **217**, 205–
 1258 222.
- 1259 Wilson, M. E., & Lokier, S. W., 2002. Siliciclastic and volcanoclastic influences on equatorial
 1260 carbonates: insights from the Neogene of Indonesia. *Sedimentology*, **49**, 583-601.
- 1261 Yılmaz Y., 1993. New evidence and model on the evolution of the southeast Anatolian
 1262 orogen. *Geological Society of America Bulletin*, **105**, 251-271.
- 1263 Zachos, J., Pagani, M., Sloan, L., Thomas, E. & Billups, K., 2001. Trends, rhythms, and
 1264 aberrations in global climate 65 Ma to present. *Science*, **292**(5517), 686-693.
- 1265 Zachos, J. C., Dickens, G. R. & Zeebe, R. E., 2008. An early Cenozoic perspective on
 1266 greenhouse warming and carbon-cycle dynamics. *Nature*, **451**(7176), 279-283.

1267

1268 **Figure Captions**

1269

- 1270 Fig. 1. Sketch map of the Mediterranean region showing key occurrences of Early, Middle
 1271 and Late Miocene reef and related facies referred to in this study, including NW Cyprus. 1.
 1272 Terra Member, Cyprus (this study and literature cited in text); 2. Zincir Kaja Platform, Mut
 1273 Basin, S Turkey (Bassant *et al.*, 2005; Janson *et al.*, 2010; Pomar *et al.*, 2012); 3. NW Gulf of
 1274 Suez (Egypt) (Schuster, 2002a, Schuster, 2002b); 4. Paros Island, Greece (Bosellini & Perrin,
 1275 2008); 5. Sirt Basin, Libya (Hladil *et al.*, 1991); 6. Dolianova, Sardinia, Italy (Cherchi *et al.*,
 1276 2000; Galloni *et al.*, 2001); 7. N Sardinia, Italy (Benisek *et al.*, 2009); 8. Bonifacio Basin,
 1277 Corsica, France (Galloni *et al.*, 2001; Tomassetti *et al.*, 2013; Brandano *et al.*, 2016); 9.
 1278 Torino Hills, Piedmont, N Italy (Chevalier, 1962); 10. Aquitaine region, S France (Chevalier,

1962; Cahauzac & Chais, 1996); 11. Dağpazarı Platform, Mut Basin, S Turkey (Bassant *et al.*, 2005; Janson *et al.*, 2010; Pomar *et al.*, 2012; Vescogni *et al.*, 2014); 12. Ziqlag Formation, Israel (Buchbinder *et al.*, 1993); 13. N Hungary (Oosterbaan, 1990); 14. Vienna Basin, Austria (Riegel & Piller, 2000); 15. Torino Hills, Piedmont, N Italy (Chevalier, 1962); 16. Djebel Chott platform, N Algeria (Belkebir *et al.*, 1994); 17. Aquitaine region, S France (Chevalier, 1962; Cahauzac & Che, 1996); 18. Valencia Region, E Spain (Calvet *et al.*, 1994); 19. Almeria, S Spain (Mankiewicz, 1996); 20. Murchas, Granada Basin, S Spain (Braga *et al.*, 1996); 21. Koronia Member, Cyprus (this study and literature cited in text); 22. Pattish Formation, Israel (Buchbinder *et al.*, 1993; Buchbinder & Zilberman, 1997); 23. Kasaba Formation, SW Turkey (Hayward *et al.*, 1996); 24. Crete, Greece (Brachert *et al.*, 2006); 25. Sirt Basin, Libya (Hladil *et al.*, 1991); 26. Salento Peninsula, Apulia, S Italy (Bosellini *et al.*, 2001; Bosellini *et al.*, 2002; Bosellini, 2006; Vescogni *et al.*, 2008)); 27. Calabria, S Italy (Chavalier, 1962; Pedley & Grasso, 1994); 28. Malta (Pedley, 1979); 29. Maiella Mountain, Abruzzo, Italy (Danese, 1999; Civitelli & Brandano); 30. Lampedusa, Pelagian Islands, S Italy (Grasso & Pedley, 1985); 31. Livorno Hills, Tuscany, Italy (Bossio *et al.*, 1996); 32. Llucmajor Platform, Mallorca, Spain (Pomar *et al.*, 1996); 33. San Miguel de Salinas Basin, SE Spain (Reinhold, 1995); 34. Almeria, S Spain (Brachert *et al.*, 1996; Mankiewicz, 1996); 35. Melilla, N Morocco (Rouchy *et al.*, 1986); 36. Granada Basin, S Spain (Braga & Aguirre, 2001). For a more complete catalogue of Mediterranean reef occurrences see Bosellini & Perrin, 2008.

Fig. 2. Outline geological map of Cyprus showing the location of the Polis graben and related reef units in NW Cyprus and other Miocene reef-related units in Cyprus (Modified from Kinnaird *et al.*, 2011). Note that many of the outcrops are dominated by reef-related talus. Inset: tectonic setting of Cyprus in the eastern Mediterranean shown (modified from Follows & Robertson, 1990; Robertson *et al.*, 1991 and Payne, 1995).

Fig. 3. Revised geological map of NW Cyprus, focussing on the Miocene facies (modified from Constantinou, 1995; Follows *et al.*, 1996 and Balmer *et al.*, 2019). Major faults of the Polis Graben are Payne & Robertson (1995).

Fig. 4. Sedimentary logs for key sections on the east and west flanks of the Polis graben, selected for age dating. See Fig. 5 for locations and the text for explanation.

Fig. 5. Topographic map of NW Cyprus (produced using ASTER Global Digital Elevation Model V003) showing the locations of the samples used for dating by different methods. Planktic foraminifera were sampled more generally (see supplementary material table S3).

Fig. 6. Stratigraphic interpretation focussing on the Miocene of NW Cyprus, as exposed on the east and west flanks of the Polis graben and in the intervening depocentre (modified after Follows *et al.* (1996), Payne & Robertson (1995), Balmer *et al.* (2019) and this study).

Fig. 7. Schematic cross-section of the northern Polis graben showing the distribution of units in relation to the present-day topography (based on Payne & Robertson, 1995, 2000). Note the Koronia Member, the Terra Member and the Pakhna Formation (undifferentiated). Key sample locations during this study are projected onto the section. See Fig. 3 for the approximate line of section.

Fig. 8. Field photographs of key Miocene facies from the west flank of the Polis graben. a, Rhythmical alternations of hemipelagic marl and chalk (above debris flow-deposit shown in b, c); correlated with the Mid-Miocene redeposited facies (see Fig. 3); Kouroulla Gorge, NW Akamas Peninsula; b, Debris-flow interbedded with hemipelagic marl and chalk (beneath a); c, Detail of the debris-flow unit in b. Based on dating, some of the intraclasts of marl and chalk (and smaller extracclasts) are likely to have been eroded from beneath the Miocene succession; d, Faviid coral fragment from the debris-flow deposit shown in b, c; e, Faviid corals in reworked Terra Member talus; Androlikou Quarry; f, Poritid coral, typical of the Koronia Member; near Akamas Village; Akamas Peninsula; g, Neptunian dykes cutting the karstified, uppermost surface of the Koronia Member, infilled with pink Pliocene marl; near Pelathousa; NE Polis graben.

Fig. 9. Detailed log of part of the interval of hemipelagic sediments and debris-flow deposits exposed in Kouroulla Gorge (see Fig. 4, log. 1). Samples were dated from below and above the discrete debris flow-deposit.

Fig. 10. Photomicrographs of two coralline algae-rich packstones with benthic foraminifera; from the west flank of the Polis graben (see Fig. 9): A. Sample TC1749, Early Miocene Terra Member; white arrowhead indicates *Eulepidina* sp.; B. Sample TC1746, Late Oligocene

neritic facies, White arrowhead indicates *Borelis melo melo*; black arrow indicates *Dendritina* sp..

Fig. 11. Sr age data for, 19 samples (in order of collection location East to West) of marl and chalk; collected from selected intervals of the Polis graben (see Fig. 5), plotted against absolute age. The determined age and the total combined error are shown for each sample. The time scale used is that of Cohen *et al.*, 2020.

Fig 12. Summary of the inferred age versus sedimentation based on this study. A. Upper Lefkara Formation (pelagic carbonates) (Lord *et al.*, 2000); B. Neritic carbonates (un-named formation) (NW Akamas Peninsula) (this study); c. Undifferentiated Pakhna Formation. (mainly marl and chalk) (this study); D. Terra Member. Reef and related neritic sediments (Follows *et al.*, 1996; this study); E. Middle Miocene redeposited and hemipelagic carbonates (this study); F. Koronia Member (Follows *et al.*, 1996; this study).

Fig. 13. Reconstruction of basin development including the coral reefs and related facies. (A) Early Miocene. The Terra Member reefs develop on a local topographic high in NW Cyprus (Akamas Peninsula), prior to formation of a well-defined graben; virtually no *in situ* reef is now preserved; (B) Late Miocene. The Koronia Member reefs develop on the upfaulted flanks of the Polis graben; *in situ* reef material is mainly restricted to the Akamas Peninsula. A is c. 10km N of section B.

Fig. 14. Benthic $\delta^{18}\text{O}$ data for the interval of the Middle Miocene Climate Transition (from the South China Sea), with the range of debris flow deposition in Kouroulla Gorge shown (after Holburn *et al.*, 2018).

Figure 1

Figure 2

32°30'E

33°E

[Click here](#)

34°F

134°30'E pdf

Figure 3

Figure 4

Figure 5

Figure 9

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Hemipelagic
marl

TC1787 -
13.53 Ma - 13.9 Ma

Debris-flow
unit

Hemipelagic
marl

TC1786 -
13.53 Ma - 13.9 Ma

Figure 10

Figure 14

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