Differentiating glacio-eustacy and tectonics; a case study involving dinoflagellate cysts from the Eocene–Oligocene transition of the Pindos Foreland Basin (NW Greece)

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ABSTRACT

In an attempt to discriminate between tectonically induced sea-level changes and glacio-eustacy, the Ekklissia and Arakthos sections (Epirus, NW Greece) are examined, applying (dinocyst) palynology, sedimentology and magnetostratigraphy. The sections, located in the Pindos Foreland Basin, both comprise the transition from pelagic limestones to hemipelagic silty clays and turbidite sandstones, reflecting the onset of flysch sedimentation as a result of the Pindos thrust activity. Despite an overall tectonic overprint, relative changes of sea level can be reconstructed, using (i) continental/marine palynomorph ratios, (ii) relative abundance of inshore and offshore dinoflagellate cysts, and (iii) taxa indicative of relatively cold and warm sea-surface temperature, that can be calibrated against the Global Polarity Time Scale (GPTS). Increased fluxes of marginal marine and continental palynomorphs coincide with colder periods on a 'third-order' scale, which thus appear to be related to glacio-eustatic trends in sea-level. The larger scale is attributed to the increasing effect of tectonics and acts on a 'second-order scale'.

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Introduction

Changes in relative sea-level caused by tectonics and by glacio-eustacy are often difficult to distinguish in the sedimentary record. High-resolution stratigraphy and detailed information on the palaeoenvironment are essential to discriminate between these possible mechanisms. Traditionally, chronostratigraphic assessment and palaeoenvir- onmental information, including proxies for, e.g., relative sea-level change, bathymetry and sea surface temperature (SST), are generated through (quantitative) micropalaeontology, notably the study of calcareous microfossils and associated stable isotope measurements ($\delta^{18}O$, $\delta^{13}C$). In tectonically active settings, however, this approach is often difficult, as the signal becomes diluted due to a high sedimentation rate as a result of a high terrigenous influx. Furthermore, increased reworking and limited preservation notoriously hamper biochronostratigraphic interpretations in such situations.

Dinoflagellate cysts are very sensitive to environmental changes, and are being successfully used in high-resolution stratigraphy (cf. Wall *et al.*, 1977; papers in Head and Wrenn, 1992; Stover and Hardenbol, 1993; Brinkhuis, 1994; Versteegh, 1994; Zevenboom, 1995). Dinoflagellates which produce organic-walled cysts, live particularly in neritic environments and consequently occur in marginal marine deposits; in more offshore settings, however, the dinoflagellate signal generally consists increasingly of transported elements. This allows detailed correlations along the inshore–offshore transect and estimates of the relative contribution of marginal marine elements. If also the proportion of terrestrial palynomorphs (sporomorphs) in offshore settings is considered, a proxy for relative sea level change can be established. In addition, the ratio between typical low-and high-latitude dinoflagellate cysts has become a well-established tool in the reconstruction of sea-surface temperature trends (e.g. Edwards *et al.*, 1991; Edwards, 1992; De Vernal, 1994; Versteegh, 1994).

In this paper we explore the potential of quantitative palynological analysis, with an emphasis on dinoflagellate cysts as a tool to discriminate between tectonically and glacio-eustatically driven sea-level change in tectonically active settings. Prerequisites for such assessment are (i) an interval in which glacio-eustacy is accepted to play an important role, (ii) an area for which a relatively high-resolution well calibrated dinoflagellate zonal framework is available for that interval, (iii) knowledge of the palaeoecology of dinoflagellates (iv) an area which qualifies as 'tectonically active' at that particular time, and (v) independent calibration of the age assessments.

These prerequisites are met in the Eocene/Oligocene (E/O) transition in the Pindos Foreland Basin (PFB) in Epirus (NW Greece). Glacio-eustatically induced sea-level changes are generally acknowledged to occur in this interval (cf. Saunders *et al.*, 1984; Miller *et al.*, 1987; Kennett and Barker, 1990) while during the late Eocene and early Oligocene, the Ionian Zone became the site of a foreland basin developing in front of the Pindos thrust (Fig. 1). This caused a pronounced shift in sedimentation from carbonates into a thick terrigenous-clastic-dominated succession (Aubouin, 1959, 1965; IGSR, 1966; Underhill, 1989). A detailed dinoflagellate zonal scheme of the Upper Eocene to Lower Miocene for the central Mediterranean was recently established by Wilpshaar *et al.* (1996). For this scheme multiple sections from central, NE and NW Italy were used and calibrated against calcareous plankton and palaeomagnetic stratigraphies on a first-order basis. For the present study a magnetostratigraphic analysis was performed to cocalibrate the chronostratigraphic interpretations.

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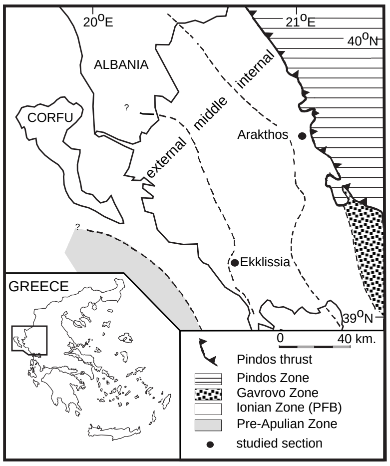

Fig. 1 Map of the Epirus area (NW Greece) and location of the investigated sections in the Ionian Zone. During the late Eocene to early Oligocene the Ionian Zone became the site of a foreland basin (Pindos Foreland Basin) which developed as a result of the Pindos thrust activity.

Materials and methods

The Epirus region in northwestern Greece (Fig. 1) is part of the NW–SE-trending Hellenides-Dinarid orogenic belt and a classic area for the study of foreland basin development (cf. Aubouin, 1959; Underhill, 1989). In the Ionian Zone (Fig. 1) of the PFB, pelagic carbonates are overlain by a sequence of terrigenous clastic deposits, often referred to as 'flysch' (Aubouin, 1959; Piper *et al.*, 1978; Fleury, 1980). Two sections, the Arakthos and Ekklissia section (Fig. 1, see also IGSR-IFP, 1966), incorporating this conspicuous change in lithology were selected for this study (Fig. 2). The Pindos Zone served as the main source area of clastic sediments of the Ionian Zone. The Arakthos section is more proximal to the thrust front than the one near Ekklissia. Both sections were sampled for palynological and palaeomagnetic analysis. The Ekklissia section used in this study slightly differs from the one mentioned in IGSR (1966). The section we used is located just North of the village of Ekklissia and reflects the complete record from limestone to flysch. Sample processing and the quantitative analysis of palynological slides, follow the methods discussed in Brinkhuis (1994). Taxonomy of dinoflagellate cysts corresponds to that in Lentin and Williams (1993), Brinkhuis and Biffi (1993) and Brinkhuis (1994). Standard palaeomagnetic cores were drilled with an electric drill. From the limestones of the lower part of the sections orientated handsamples were taken. All samples were progressively demagnetized, either by applying alternating fields or stepwise thermal demagnetization. The natural remanent magnetization (NRM) was measured on a high-sensitivity 2G Enterprises cryogenic magnetometer, using DC squids.

Sea-level and sea surface temperature reconstructions

Traditionally the fraction of terrestrial palynomorphs (sporomorphs) relative to the total amount of palynomorphs, is used as a proxy for continental influence. Some authors (e.g. Traverse and Ginsburg, 1966) also use this ratio as an indication of relative sea-level change. In this paper the continental–marine proxy (CM) is expressed as the percentage of pollen and spores in the total palynomorph assemblage:

$$\mathrm{CM} = \frac{\mathrm{C}}{\mathrm{C} + \mathrm{M}} \qquad (1)$$

in which C = continental palynomorphs (pollen and spores) and M = marine palynomorphs (dinoflagellate cysts). Brinkhuis (1994) proposed a model for the distribution of dinoflagellate cyst groups across the Trento (NE Italy) shelf during late Eocene to early Oligocene times. The model is based on known (Recent) and empirically established (palaeo)ecological information and distribution patterns of quantitatively important dinoflagellate cyst groups. In order to interpret the dinoflagellate cyst association, division into four ecological groups was made, namely (i) taxa representing restricted marine to inner neritic watermasses (RM), (ii) inner neritic taxa (IN), (iii) outer neritic taxa (ON), and (iv) oceanic taxa (OC) (Table 1). Both the CM ratio and fluctuations in the dinoflagellate cyst ecological groups may be regarded to primarily reflect the distance to the coast, which may be interpreted in terms of relative changes in sea level. The reconstruction of trends in SST is based on relative abundance of the oceanic genera *Impagidinium* and *Nematosphaeropsis*. Here all *Impagidinium* spp. except for *Impagidinium pallidum* and *Impagidinium velorum* are considered to represent low-latitude, warm waters (cf. Brinkhuis and Biffi, 1993). The latter two taxa are regarded to represent the influence from colder watermasses. This assessment is based largely on present-day distributions, and, in the case of *Impagidinium velorum*, on fossil evidence (cf. Bujak, 1984). All the taxa used for the SST-proxy range through the investigated interval. The following equation representing relative SST (Zevenboom, 1995), is used:

Results and discussion

Dinoflagellate cysts

All samples contain rich and relatively well-preserved palynological associations except for a few palynologically barren samples in the lower part of the Ekklissia section. Most dinoflagellate associations are well diversified and characterized by high percentages of *Spiniferites*/*Achomosphaera* spp., *Operculodinium* spp., and *Systematophora* spp. Furthermore, *Impagidinium* spp. and *Nematosphaeropsis* spp. are common in the lower and middle parts of the sections. *Deflandrea* spp., *Systematophora* spp. and *Homotryblium* spp., show higher percentages in the upper parts. Occasionally, *Areosphaeridium* spp., *Thalassiphora pelagica,* and *Tectatodinium* spp. are abundant as well.

The qualitative dinoflagellate cyst distribution allows the recognition of the Lower Oligocene Adi, Rac and Cin Mediterranean dinocyst Biozones of Brinkhuis and Biffi (1993), spanning parts of Chron C13r–C12r (34.0–32.5 Ma, Berggren *et al.*, 1995) in both sections. At Arakthos, the uppermost Eocene Aal and lowermost Oligocene Gse Biozone are represented also (Fig. 2).

Palaeomagnetism

The ChRM directions show on average a 48° clockwise tectonic rotation for the Arakthos section, which is in good agreement with the results from Horner and Freeman (1983) and Kissel and Laj (1988) who report rotations of 45–50°. This large rotation of the ChRM enables us to distinguish between a primary normal direction and a normal overprint. The presence of both normal and reversed directions confirms the primary origin of the magnetization. Unfortunately, some samples show

$$\mathrm{SST} = \frac{^{2}\Sigma\,(I.velorum + I.pallidum) + \Sigma\ Nematospaeropsis\ spp.}{\Sigma Impagidinium\ spp. + \Sigma\ Nematospaeropsis\ spp.} \qquad (2)$$

such a low intensity that no reliable directions could be determined (e.g. at Ekklissia below and above a normal polarity interval). The ChRM directions of the Arakthos section record allow the recognition of a well-defined normal polarity interval, comprising the upper part of the Gse Zone, the whole Adi Zone and the lower part of the Rac Zone (Fig. 2). Despite some uncertainties, the results from the Ekklissia section indicate a reversed polarity for the Cin Zone and a normal polarity for the lower part of the Rac Zone (Fig. 2). Comparison of the biostratigraphic and magnetostratigraphic results with the scheme of Wilpshaar *et al.* (1996), indicates that the normal polarity interval in both sections represents Chron C13n. Palaeomagnetic data thus confirm that both sections are largely time-equivalent, and, moreover, they indicate that the transition from limestones to terrigenous clastic deposits is older at Arakthos than at Ekklissia (Fig. 2).

Sea-surface temperature and sea-level reconstructions

Trends in dinoflagellate cyst ratios and ecological groups can be interpreted as fluctuations in continental influence, relative distance to the coast and sea-surface temperatures (Fig. 2). The lower parts of the sections are dominated by outer neritic and oceanic taxa, indented by small excursions of restricted marine and inner neritic ecological groups, reflecting relatively outer neritic to open marine conditions for the lower part of both sections. An increasing CM proxy, in both sections, mimics the shift from carbonates to terrigenous clastic sedimentation. Similarly, an upward increase of restricted marine and inner neritic dinoflagellate cysts indicates increasing influence of marginal marine settings. On average, the percentages of sporomorphs and marginal marine dinoflagellate groups is higher at Arakthos than at Ekklissia, reflecting the more distal setting of the latter. At Arakthos, where the uppermost Eocene is identified, three distinct intervals are recorded in the CM curve; the first associated with the Aal and Gse zones ($<20\%$ continental palynomorphs), the second within the Adi and Rac and lower part of the Cin Zones (20–40% continental palynomorphs), and the third within the Cin Zone ($>40\%$ continental palynomorphs). The distribution pattern of the oceanic ecological group shows a similar three fold division.

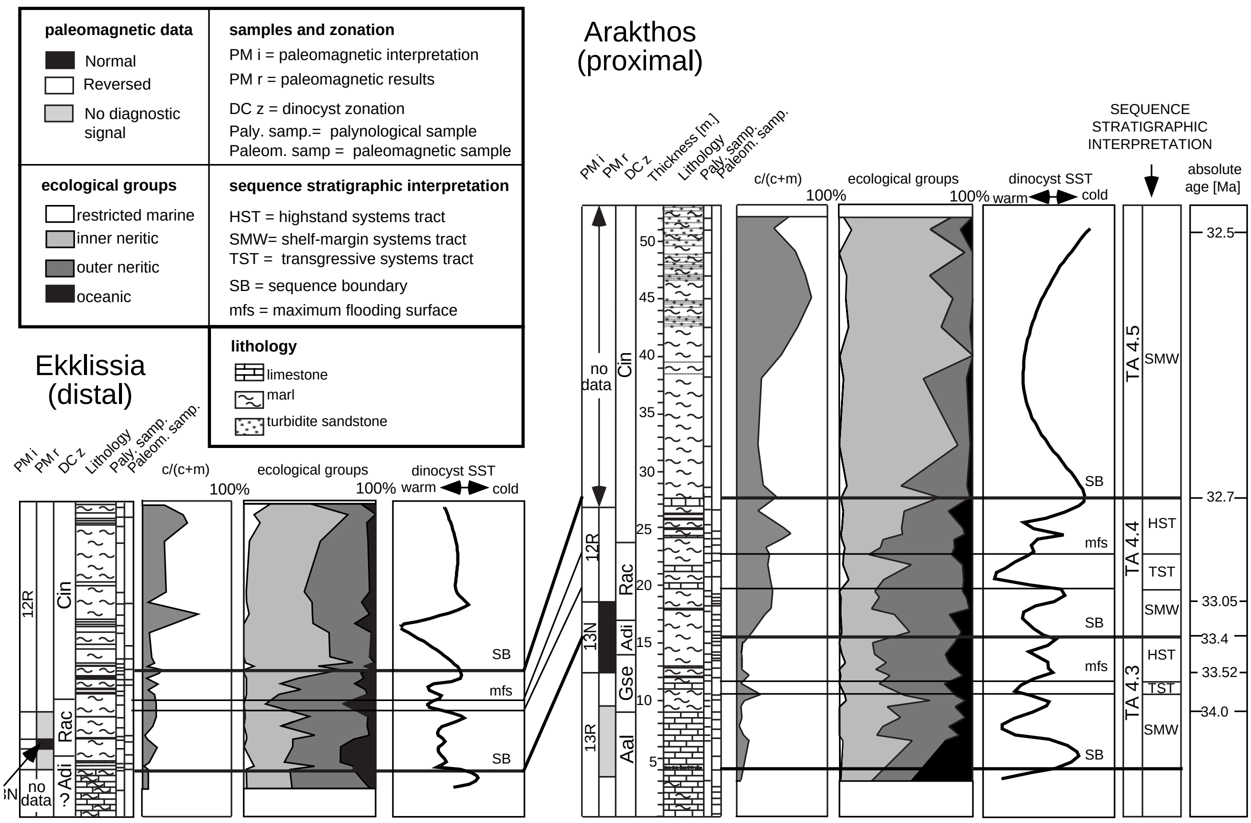

Fig. 2 The Arakthos and Ekklissia sections, Continental/Marine (C/(C + M)) ratio, dinoflagellate eco-groups, dinocyst sea-surface temperature (SST) reconstruction, dinoflagellate-cyst zonal assignments, palaeomagnetic zonal assignments, sequence-stratigraphic interpretation and correlation to the cycles of Haq *et al.* (1988).

Table 1 Based on empirically established (palaeo) ecological information (Brinkhuis, 1994), the dinoflagellate cyst association is divided into four ecological groups. The subdivision is on genus level, except for *Spiniferites* and *Hystrychokolpoma* which were subdivided up to species level dinoflagellate cyst ecological groups

Restricted	Inner neritic	
Eocladopyxis spp.	*Areoligera* spp.	*Hystrichokolpoma* spp. (pp.)
Homotryblium spp.	*Cordosphaeridium* spp.	*Operculodinium* spp.
Phthanoperidinium spp.	*Deflandrea* spp.	*Schematophora* spp.
Polysphaeridium spp.	*Glaphyrocysta* spp.	*Spiniferites* spp. (pp.)
Wetzeliella cpx.	*Heteraulacacysta* spp.	*Systematophora* spp.
oceanic	outer neritic	
Impagidinium spp.	*Ennadeacysta* spp.	*Spiniferites* spp. (pp.)
Nematosphaeropsis spp.	*Hemiplacophora* spp.	*Stoveracysta* spp.
	Hystrichokolpoma spp. (pp.)	*Tectatodinium* spp.
	Reticulatosphaera spp.	*Thalassiphora* spp.

Slightly below the Rac/Cin zonal boundary (middle Early Oligocene) the combined outer neritic and oceanic dinoflagellate cyst group reach maximum values of $\approx 80\%$ of the total association in both sections. Slightly higher in the sections, the composition of the dinoflagellate cyst association changes abruptly and becomes dominated by inner neritic taxa. This sudden change in composition occurs in both sections at the base of the Cin zone and is regarded to be isochronous. Remarkably, this change in the dinoflagellate cyst assemblage seems to be unrelated to the terrestrial influx, since the CM ratio remains virtually constant in this interval. The upper part of both sections, assigned to the Cin Zone, is characterized by high percentages of both the combined restricted/inner neritic group and sporomorphs, indicating that marginal marine and continental influxes became overwhelmingly dominant.

Sequence stratigraphy

Following the sequence stratigraphic model of Vail *et al.* (1977) and applying the CM ratio and dinoflagellate data combined with lithological changes, a tentative subdivision into system tracts is proposed. Using also the available dinoflagellate zonal scheme, three third-order cycles can be recognized at Arakthos (Fig. 2). The oldest cycle starts at the base of the limestone channel and ends just before the Adi–Rac transition. The top of the second cycle is drawn just above the last pelagic limestone layer, at the base of a thick succession of marls, silts and eventually, coarser grained sandy turbidites.

At Ekklissia, the more condensed section, changes are less clear, notably in the lower part of the succession. A first sequence boundary is placed at the base of the inception of more marly sedimentation in the Adi zone. Similar to Arakthos, the top of this cycle is drawn just above the last pelagic limestone layer, at the base of the succession of marls, silts and coarser grained sandy turbidites. At the Eocene/Oligocene transitional interval, Haq *et al.* (1988) also recognize three third-order cycles (TA4.3, TA4.4 and TA4.5); that they were recognized in central and northeast Italy with the use of dinoflagellate palynology, and the sequence boundaries occur in the same biozones (Brinkhuis and Biffi, 1993; Brinkhuis, 1994), stresses their inter-regional character. Although the cycles have been tectonically enhanced (TA4.5) or subdued (TA4.3/TA4.4), their position seems to agree with the Haq *et al.* (1988) chart for the late Eocene and early Oligocene.

The concomitant overall change of both lithology and palynology indicates that tectonics play an important role. However, it appears that within this larger scaled trend, shorter termed cyclicities occur, which, by using the biochronostratigraphy, can be attributed to the so-called 'third order' cycles *sensu* Haq *et al.* (1988). The larger scaled trend may thus be attributed to second-order cyclicity.

Tectonics vs. glacio-eustacy

Between the sections the alternating pattern of colder and warmer intervals can be reasonably correlated (Fig. 2). In the Ekklissia section, two intervals with relatively cold SSTs are recognized, one in the Adi and one during lower part of the Cin biozone. At Arakthos, three intervals with relatively cold SSTs are recognized, namely besides the Adi and lower Cin biozones, but also during the Aal biozone. Following the Vail *et al.* (1977) sequence stratigraphic model, it may be anticipated that if a relationship between third-order cyclicity and glacio-eustatic cycles exists, SST values are low during late HST and (early) LST. This appears to be the case in our study of the Arakthos and Ekklissia sections. Hence, our records support an underlying glacio-eustatic mechanism as the cause for sea-level lowering and increased transportation of marginal marine elements, with a cyclicity of ≈ 500 Kyr (third-order). The lower order trend does not show a relationship with cool/warm cycles, although it clearly has impact on the composition of the palynological associations. This lower, second-order trend with a cyclicity of > 1 Myr, may thus be ascribed to large-scale compressional tectonics.

Conclusions

The transition from limestone sedimentation into siliciclastic sedimentation (flysch) in the Arakthos and Ekklissia sections from the Pindos Foreland Basin occurred at 33.6–32.5 Ma, following the timescale of Berggren *et al.* (1995), using dinoflagellate cyst zonation and magnetostratigraphy. The lower part of the transition is characterized by relatively high abundances of outer neritic and oceanic taxa, whereas the upper part is dominated by restricted and inner neritic marine taxa. In addition, relative percentages of terrestrial palynomorphs increases significantly upsection. In both sections increased fluxes of transported material, taken as indicative for sea-level fall coincide with relatively cold dinoflagellate-based SSTs on a third-order scale *sensu* Haq *et al.* (1988). In both sections there seems to be no obvious relationship between SST trends and the larger scale (second-order) trend as evidenced by the sporomorph and inshore/offshore dinoflagellate ratios. It is considered that this larger scale trend is the expression of the increasing effects of tectonics (i.e. approach of the Pindos thrust front), while the smaller scale cyclicity corresponds to the third-order cycles of Haq *et al.* (1988). The chronostratigraphical position of the sequences matches those reported by these authors, and may be ascribed to glacio-eustacy. Therefore, it is concluded that the trends and fluctuations in inshore/offshore ratios in the sections mirror the interference of climatically controlled (third-order) and tectonically induced (second-order) sea-level fluctuations. This study demonstrates the potential of quantitative dinoflagellate studies as a tool for high-resolution stratigraphic and palaeoenvironmental analysis.

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References

Aubouin, J., 1959. Contribution à l'étude géologique de la Grece septentrionale: les confirm de l'Epire et de la Thessalie. *Ann. Géol. Pays Hell.*, **10**, 483pp.

Aubouin, J., 1965. Contribution à l'etude geologique de la Grece septentrionale: les confirm de l'Epire et de la Thessalie. In: *Geosynclines* (Aubouin, J., ed.). Elsevier, Amsterdam, 335pp.

Berggren, W.A., Kent, D.V., Aubry, M.P. and Hardenbol, J., 1995. Geochronology, time scales and global stratigraphic correlation. *Spec. Publ. Soc. econ. Paleont. Miner., Tulsa*, **54**, 386pp.

Brinkhuis, H., 1994. Late Eocene to Early Oligocene dinoflagellate cysts from the Priabonian type area (Northeast Italy): biostratigraphy and paleoenvironmental interpretation. *Palaeogeogr. Palaeoclim. Palaeoecol.*, **107**, 121–163.

Brinkhuis, H. and Biffi, U., 1993. Dinoflagellate cyst stratigraphy of the Eocene/Oligocene transition in central Italy. *Mar. Micropaleont.*, **22**, 131–183.

Bujak, J.P., 1984. Cenozoic dinoflagellate cysts and acritarchs from the Bering Sea and northern Pacific, DSDP Leg 19. *Micropaleontology*, **30**(2), 180–212.

De Vernal, A., 1994. Dinoflagellate cyst distribution in high-latitude marine environments and quantitative reconstruction of sea-surface salinity, temperature, and seasonality. *Can. J. Earth Sci.*, **31**, 48–62.

Edwards, L.E., 1992. New semiquantitative (paleo) temperature estimates using dinoflagellate cysts, an example from the North Atlantic ocean. In: *Neogene and Quaternary Dinoflagellate Cysts and Acritarchs* (M.J. Head and J.H. Wrenn, Eds), pp. 69–87. AASP Foundation, Dallas, TX.

Edwards, L.E., Mudie, P.J. and De Venal, A., 1991. Pliocene paleoclimatic reconstruction using dinoflagellate cysts: comparison of methods. *Quat. Sci. Rev.*, **10**, 259–274.

Fleury, J.J., 1980. Les zones de Gavrovo-Tripolitza et du Pinde-Olonos (Grèce continentale et Péloponnèse du Nord): Evolution d'une plate-forme et d'un bassin dans leur cadre alpin. *Soc. Géol. du Nord*, **4**.

Haq, B.U., Hardenbol, J., Vail, P.R., 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea level change. In: *Sea Level Changes: an Integrated Approach* (C.K. Wilgus and B.S. Hastings, Ed.). *Spec. Publ. Soc. econ. Paleont. Miner., Tulsa*, **42**, 71–108.

Head, M.J. and Wrenn, J.H. (eds), 1992. *Neogene and Qarternary Dinoflagellate Cysts and Acritarchs*. American Association of Stratigraphic Palynologists Foundation, Dallas, TX.

Horner, F. and Freeman, R., 1983. Palaeomagnetic evidence from pelagic limestones for clockwise rotation of the Ionian zone, western Greece. *Tectonophysics*, **98**, 11–27.

IGSR -I.F.P., 1966. *Etude Géologique De l'Epire (Grèce Nord-Occidentale)*. Institute Français du Petrole, Paris, 306pp.

Kennett, J.P., Barker, P.F., 1990. Latest Cretaceous to Cenozoic climate and oceanographic developments in the Weddell Sea, Antartica: An Ocean-Drilling Perspective. *Proc. Ocean drill. Prog., Sci. Res.*, 113, 937–960.

Kissel, C. and Laj, C., 1988. The Tertiary geodynamical evolution of the Aegean arc: a paleomagnetic reconstruction. *Tectonophysics*, **146**, 183–201.

Lentin, J.K. and Williams, G.L., 1993. *Fossil Dinoflagellates: Index to Genera and Species 1993*. American Association of Stratigraphic Palynologists Contributions Series, 28. AASP Foundation. Dallas, TX, 856pp.

Miller, K.G., Fairbanks, R.G. and Mountain, G.S., 1987. Tertiary oxygen isotope synthesis, sea level history and continental margin erosion. *Paleoceanogr.*, **2**(1), 1–19.

Piper, D.J.W., Panagos, A.G. and Pe, G.G., 1978. Conglomeratic Miocene flysch, western Greece. *J. Sedim. Petrol.*, **48**(1), 117–126.

Saunders, J.B., Bernouilli, D., Müller-Merz, E., Oberhänsli, H., Perch-Nielsen, K., Riedel, W.R., Sanfilippo, A. and Torrini, R. Jr, 1984. Stratigraphy of the Late Middle Eocene to Early Oligocene in the Bath Cliff section, Barbados, West Indies. *Micropaleontology*, **30**(4), 390–425.

Stover, L.E. and Hardenbol, J., 1993. Dinoflagellates and depositional sequences in the lower Oligocene (Rupelian) Boom clay formation, Belgium. *Bull. Belg. Verenig. Geol.,*, **102**(1–2), 5–77.

Traverse, A. and Ginsburg, R.N., 1966. Palynology of the surface sediments of Great Bahama Bank as related to water movements and sedimentation. *Mar. Geol.*, **4**, 417–459.

Underhill, J.R., 1989. Late Cenozoic deformation of the Hellenide foreland, western Greece. *Bull. Geol. Soc. Am.*, **101**, 613–634.

Vail, P.R., Mitchum, R.M. Jr, Todd, R.G., Wildmier, J.M., Thompson, S. III, Sangree, J.B., Bubb, J.N. and Hatfield, W.G., 1977. Seismic stratigraphy and global changes of sea level. In: *Seismic Stratigraphy-Applications to Hydrocarbon Exploration* (C.E. Payton, Ed.). *Mem. Am. Ass. Petrol. Geol.*, **26**, 49–212.

Versteegh, G.J.M., 1994. Recognition of cyclic and non-cyclic environmental changes in the Mediterranean Pliocene; a palynological approach. *Mar. Micropaleont.*, **23**, 147–171.

Wall, D., Dale, B., Lohmann, G.P. and Smith, W.K., 1977. The environmental and climatic distribution of dinoflagellate cysts in modern marine sediments from regions in the north and south Atlantic oceans and adjacent seas. *Mar. Micropaleont.*, **2**, 121–200.

Wilpshaar, M., Santarelli, A., Brinkhuis, H. and Visscher, H., 1996. Dinoflagellate cysts and mid-Oligocene chronostratigraphy in the central Mediterranean region. *J. Geol. Soc. London*, **153**, 553–561.

Zevenboom, D., 1995. Dinoflagellate cysts from the Mediterranean Late Oligocene and Miocene. Unpubl. doctoral dissertation, Utrecht University, The Netherlands, 221pp.

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