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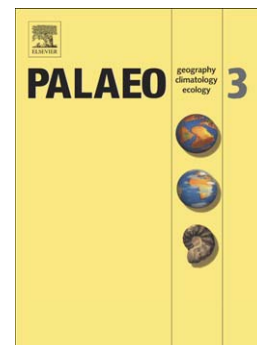http://dx.doi.org/doi:10.1016/j.palaeo.2016.11.043

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Reconstructing Cenozoic vegetation from proxy data and models – a NECLIME synthesis (Editorial)

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1. Introduction

The Cenozoic era is marked by a gradual cooling of Earth's climate (Zachos et al., 2001; Zachos et al., 2008) in parallel to a decrease of the atmospheric partial pressure of CO_2, as documented by proxy records (Pagani et al., 1999, 2005; Pearson and Palmer, 2000; Zachos et al., 2008; Kürschner et al., 2008; Pearson et al., 2009; Doria et al., 2011). Climate was particularly warm near 50 Ma, an episode termed the early Eocene climatic optimum. At this time oxygen isotopic data indicate deep oceanic temperature ~12 °C warmer than today (Zachos et al., 2001), suggesting an equivalent warming of sea surface temperatures in the high latitudes of the Northern Hemisphere where deep waters are formed. Then, at the onset of the Oligocene, climate cooled rapidly causing the development of the Antarctic ice sheet, probably as a response to a significant decrease in atmospheric CO_2 (DeConto and Pollard, 2003; Zachos and Kump, 2005; Pearson et al., 2009). At the end of the Oligocene, global climate warmed again (De Man and Van Simaeys, 2004; Villa and Persico, 2006) and this warming culminated in the Miocene near 15 Ma, with another climate optimum, the so-called mid-Miocene climatic optimum (Zachos et al., 2001). This warm phase is characterized by a heavy carbon isotopic composition of deep sea carbonate sediments, suggesting high deposition fluxes of organic matter, either from the marine realm (Vincent and Berger, 1985) or from the land (Diester-Haass et al., 2009, 2013). This phase ended with the middle Miocene climate transition, between 14.2 and 13.8 Ma, when the Antarctic ice sheet started to grow again (Shevenell et al., 2004). This transition initiated a global and progressive cooling of the planet that persisted through the late Miocene, the Pliocene, and the Pleistocene until the present.

Cenozoic cooling is generally attributed to the decrease in atmospheric CO_2 over the same period. However, other factors have likely been important too, such as the change in continental positions, the opening or closure of marine seaways, and the uplift of mountain ranges, such as the Himalaya. The impact of mountain uplift has been widely discussed in the literature (see, e.g., pioneer papers by Raymo et al., 1988; Molnar and England, 1990; Raymo and Ruddiman, 1992). Impacts of uplift on climate can be direct through changes, for instance, in the atmospheric circulation (e.g., Broccoli and Manabe, 1992) or indirect through enhancement of erosion and chemical weathering that ends in a decrease of the atmospheric CO_2 mixing ratio (e.g., Raymo and Ruddiman, 1992; Goddéris and François, 1995, 1996; Garzione, 2008). Climate evolution over the Cenozoic is also characterised by a progressive increase of the equator-pole temperature gradient. Warmer climates of the past indeed seem to exhibit very weak latitudinal temperature gradients (e.g., Barron, 1987; Jiménez-Moreno and Suc, 2007). Over the Cenozoic, climate also showed a clear trend towards a globally drier state, as indicated by the worldwide development and expansion of grassland and desert ecosystems in the Neogene (Retallack, 2001). Through climate-vegetation feedbacks, this expansion of grasslands and deserts at the expense of forests may have significantly amplified the global Cenozoic cooling (e.g., Dutton and Barron, 1997).

Plant remains, both mega- and microfossils, are widely used as palaeoclimate indicators over the continents. Mosbrugger et al. (2005) have, for instance, reconstructed the climate evolution of Central Europe over the last 45 million years from palaeobotanical data. Their reconstruction is in general agreement with trends recorded in the marine isotopic data (Zachos et al., 2001). Besides climate, palaeobotanical data can also be used to infer vegetation distribution and ecosystem

structure in the past. This is the focus of this special issue of *Palaeogeography, Palaeoclimatology, Palaeoecology*, which aims at quantifying vegetation changes throughout Cenozoic times using proxy data and models. This special issue is organised within the framework of NECLIME, an international project briefly outlined below. This special volume is largely a collection of papers presented at two workshops organised by NECLIME: a session entitled *Cenozoic vegetation quantification with models and proxy data (a NECLIME and ROCEEH contribution)* within the 9th European Palaeobotany and Palynology Conference, Padova, Italy, 26-31 August, 2014, and the *NECLIME 2014* annual meeting held in Izmir, Turkey, 19-22 October, 2014. After a short introduction to NECLIME, we present below the main methods used to reconstruct palaeovegetation, as an introduction to the papers in this special issue.

2. The NECLIME project

The international open research network *NECLIME – Neogene Climate Evolution in Eurasia –* was established in 1999 in order to promote studies on climate change in Eurasia during the Neogene and the impact of climate change on the biosphere. The steadily growing network is co-ordinated by groups of researchers, and currently has 142 members in 36 countries. NECLIME holds annual meetings, has working groups and advisers for specific topics, thus promoting scientific exchange, joint projects, and integration of the results obtained from research across various disciplines. NECLIME records are made available in Pangaea (www.pangaea.de). The publication policy of the network includes the release of special issues. The current issue is the 5th in a series of volumes published in *Palaeogeography, Palaeoclimatology, Palaeoecology*, (2007; 2011), the *Turkish Journal of Earth Sciences* (2012), and *Palaeoworld* (2013).

NECLIME research focuses on the reconstruction of Neogene palaeoenvironments of Eurasia and especially on interactions between the geo- and biosphere. This research includes proxy-based reconstructions of past palaeoclimate, palaeogeography, ecosystems and their diversity, and atmospheric CO_2, with a clear emphasis on continental archives. Studies contributing to the network employ multiple, quantitative techniques applicable on various proxies such as palaeoflora, vertebrates and invertebrates complemented by geological and geochemical data. Partly, these techniques were developed by members of NECLIME, inspired by joint research within the network. Since the foundation of NECLIME, modelling studies add to the research of the network because they shed light on the processes behind the recorded proxy-based patterns. Modelling approaches carried out in the framework of NECLIME include ocean, atmosphere and biosphere on global or regional scales.

The close interplay between proxy data and modelling not only provides a more complete understanding of the past along the later Neogene cooling trend, including the transition into the global ice-house in the earlier Pleistocene, but may also lead to a better assessment of anticipated changes. Combining a palaeogeography relatively close to present and globally warmer conditions, most Neogene time spans are suited for case studies related to model performance regarding the simulation of proxy-based patterns.

Emphasis on quantitative reconstructions of past climates and ecosystems has driven the development and refinement of methodological approaches that has always been a primary focus of the NECLIME network. Several, now well-tested methodologies were designed within the context of NECLIME. These include the IPR (Integrated Plant

Record), the PCS (Plant Community Scenarios), the PFT (Plant Functional Type) Approach, the CA$_{eco}$ Approach and the CDA (micromammal-based Climate-Diversity Approach; van Dam and Utescher, 2016). The first four methods are designed for ecosystem reconstruction. They are summarised in the next section. Other quantitative techniques were upgraded and expanded in studies related to NECLIME (CLAMP - Climate Leaf Analysis Multivariate Program, e.g., Tao et al., 2013; Spicer et al., 2009; 2011; Teodoridis et al., 2011a; CA -Coexistence Approach, e.g., Utescher et al., 2014).

3. Reconstructing palaeovegetation and palaeoenvironment from proxies and models

To reconstruct palaeovegetation based on compilations of fossil floras, several methods have been developed aiming at standardised procedures, to provide reproducible and comparable results, and to enable spatial interpolations of vegetation cover. Those methods vary mainly in the scale of their spatial scope and range from the reconstruction of local plant formations to large-scale biome level development.

The aim of the *PCS (Plant Community Scenario) approach* (Martinetto and Vassio, 2010; Vassio and Martinetto, 2012) is to reconstruct and compare *local vegetation formations*. Originally PCS was developed for interpreting fossil fruit and seed assemblages in a standardised quantitative way as a simplified 2D sketch (PCS), similar to a vegetation transect, considering growth forms and ecological preferences. PCS has also been applied to pollen (Martinetto et al., 2012; Vassio, 2012) and leaf assemblages (Vassio, 2012) (see Teodoridis et al., this issue).

The *IPR (Integrated Plant Record) vegetation analysis* is a semi-quantitative technique developed by Kovar-Eder and Kvaček (2003) to reconstruct and map *regional zonal vegetation* (Kovar-Eder and Kvaček, 2007; Kovar-Eder et al., 2008; Teodoridis et al., 2011b), based on plant taxonomy, physiognomy, and autoecological characteristics of the fossil taxa from leaf, carpological, wood, and pollen assemblages. Kayseri Özer (this issue) uses IPR analysis to study plant evolution in Anatolia from the late Oligocene to the Pliocene. Also Bondarenko et al. and Teodoridis et al. (both this issue) apply this approach in comparison to other methods.

The *PFT (Plant Functional Type)* approach (Utescher et al., 2007; François et al., 2011; Popova et al., 2013) aims at reconstructing *regional biomes.* The biomisation method of Prentice et al. (1996) and Ni et al. (2010) is restricted to pollen data, whereas the approach of François et al. (2011) can be applied to all plant organs. The assignment of PFTs to fossil taxa allows for the abstraction from taxonomy to universal plant traits. The method provides a likelihood level of presence, as well as a diversity index, for all reconstructed PFTs at each studied site. Such a PFT-level vegetation reconstruction has the advantage of being easily comparable with the results of vegetation models. Several contributions within this issue use the PFT approach (Bondarenko et al.; Popova et al.; Henrot et al.).

Another rather large-scale approach is the *CA$_{eco}$* approach (Bruch et al. 2012), i.e., the application of the *Coexistence Approach* technique on vegetation parameters such as *leaf area index and vegetation cover* to obtain quantified, globally comparable data on productivity and canopy density (see Bondarenko et al., this issue; Popova et al., this issue).

Palaeovegetation can also be reconstructed from vegetation models forced with climate model outputs. Although more empirical species distribution models could be used for this purpose, it is mostly *dynamic vegetation models (DVMs)* that have been applied to reconstruct pre-Pleistocene vegetation (François et al., 2006, 2011; Lunt et al., 2007; Henrot et al., 2010; Pound et al., 2011; Forrest et al., 2015). The use of DVMs is a very powerful method for palaeovegetation reconstruction, since it provides not only *large-scale vegetation distribution*, but also *many vegetation attributes*, such as leaf area index, gross and net primary productivity, biomass, soil organic carbon storage, etc. However, the reliability of the results depends on the quality of the climate model reconstructions used as inputs to the DVM. It is thus necessary to validate these model results with vegetation reconstructions from other methods (see Henrot et al., this issue; Fer et al., this issue).

Finally, palaeobotanical data can also be used to reconstruct *environmental parameters* that control vegetation development. For instance, stomatal data from fossil leaves is now widely used to reconstruct palaeo-CO_2 levels (e.g., Kürchner et al., 2008; Franks and Beerling, 2010). This method is exploited in this volume and expanded by the use of leaf-level ecophysiological modelling (Sun et al., this issue; Roth-Nebelsick and Konrad, this issue). Another example of environmental reconstruction is the possibility that palaeobotanical data enables the study of habitats of ancient hominids (Rudaya et al., this issue).

All these methods have to deal with the challenge of different signals provided by the different plant organs – fossil leaf assemblages over-represent arboreal vegetation whereas pollen assemblages usually show a greater diversity of herbs. Because each plant organ has its own characteristics in regard to production, taphonomy, and preservation, all methods struggle to truly integrate those data. It is obvious that the information provided by the different plant organs are complementary and must be integrated, but integration has to be done with care (as discussed by Popova et al., this issue).

This volume contains 16 contributions using the above methods to reconstruct past vegetation and environments for different epochs of the Cenozoic. The order of contributions follows the geological time sequence, starting with the papers dealing with most remote times or spanning a large portion of the Cenozoic era. All epochs from the Oligocene to the Pleistocene are represented. These studies encompass many spatial scales, from the regional to the global. Thus all continents are covered, although the emphasis for most studies is on the Eurasian continent, consistent with NECLIME objectives.

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