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THE PIONEERING CONTRIBUTIONS AND LEGACY OF WALDO H. ZAGWIJN (1928–2018)

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ABSTRACT**:** Professor Dr. Waldo H. Zagwijn passed away on 26 June, 2018, in his ninetieth year. His thesis research (Zagwijn, 1960) stimulated palynological investigations into the Pliocene and early Quaternary, and caused a fundamental shift in our understanding of the transition from the warm and relatively stable climate of the late Neogene to the extreme glacial–interglacial oscillations of the early Quaternary. Distinct in several aspects from the usual methodologies of that time, Zagwijn's approach can be summarized as:

- focusing on establishing the botanical identification of pollen grains, following the guiding approach of his supervisor F. Florschütz, using botanical nomenclature to highlight these identifications and clarify relationships between botany and the earlier artificial pollen nomenclature;
- comprehensive and persistent attention to plant macroremains (fruits, seeds, etc.; Zagwijn, 1990) as a mean of integrating classical palaeobotany with modern palynology;
- palaeoenvironmental interpretations informed by a deep understanding of modern plant ecology and associations;
- leading investigations in the field, and paying special attention to stratigraphic correlations between (onshore and offshore) boreholes and exposed sections in quarries, using a range of available proxies including heavy mineral analysis.

Waldo H. Zagwijn was a visionary in realizing how modern palynology can be used for vegetational and climatic reconstructions in the Neogene, and indeed as far back as Paleogene times.

Keywords: pollen analysis, palaeovegetation, climatostratigraphy, Pliocene–Pleistocene boundary, glacials–interglacials

1. MODERN PALYNOLOGY AND ITS CONTRIBUTION TO GLOBAL CLIMATOSTRATIGRAPHY

Using the methodological novelties detailed above, Zagwijn's thesis identified a pronounced cooling event (marked by the establishment of tundra-like vegetation in The Netherlands) separating the Reuverian and Tiglian continental regional stages, and he identified this as the Praetiglian, a stage named earlier by Van der Vlerk & Florschütz (1953) from the classic Dutch-German border area. Zagwijn had in fact discovered the onset of pronounced glacial–interglacial cycles in the Northern Hemisphere. This immediately brought his work to the attention of the international scientific community. This first major contribution of Zagwijn was to show how the evolution of vegetation and climate of North Europe progressed cyclically from subtropical to warm-temperate and glacial conditions. It resulted in the establishment of a robust climatostratigraphy with the possibilities of long-distance correlation (Van der Hammen et al., 1971), based on botanical pollen classification and counting, rather than the now outdated palynostratigraphic method constructed on the presence or absence of fictitious species.

Aiming to obtain independent chronological control for the record of climate changes, Zagwijn proposed correlations with the Mediterranean succession, and this included locating the Pliocene–Pleistocene boundary, which had been under discussion since 1948, at the Piacenzian–Calabrian contact (Zagwijn, 1974, 1975a). Simultaneously, Zagwijn explored magnetostratigraphy as a mean to calibrate climate evolution with the global timescale (Zagwijn, 1975b) and paid special attention to mammal biochronology in support of regional correlations (e.g., Van der Meulen & Zagwijn, 1974). Oxygen isotope curves showed that the Praetiglian glacial stage occurred in what was then considered the late Pliocene (Shackleton & Opdyke, 1977; Blanc et al., 1983; Shackleton et al., 1984), as supported by subsequent pollen records in the northwestern Mediterranean region (Cravatte & Suc, 1981; Suc & Cravatte, 1982; Suc, 1984). As a consequence, a reliable climatostratigraphic relationship between The Netherlands and the Mediterranean was established and the first significant cooling in the Northern Hemisphere (onset of tundra-like vegetation to the north, and steppe vegetation to the south) was placed near the Gauss–Matuyama reversal (Suc & Zagwijn, 1983). The discovery confirmed the value of pollen records for long-distance correlation and strengthened the chronological framework for climate change in

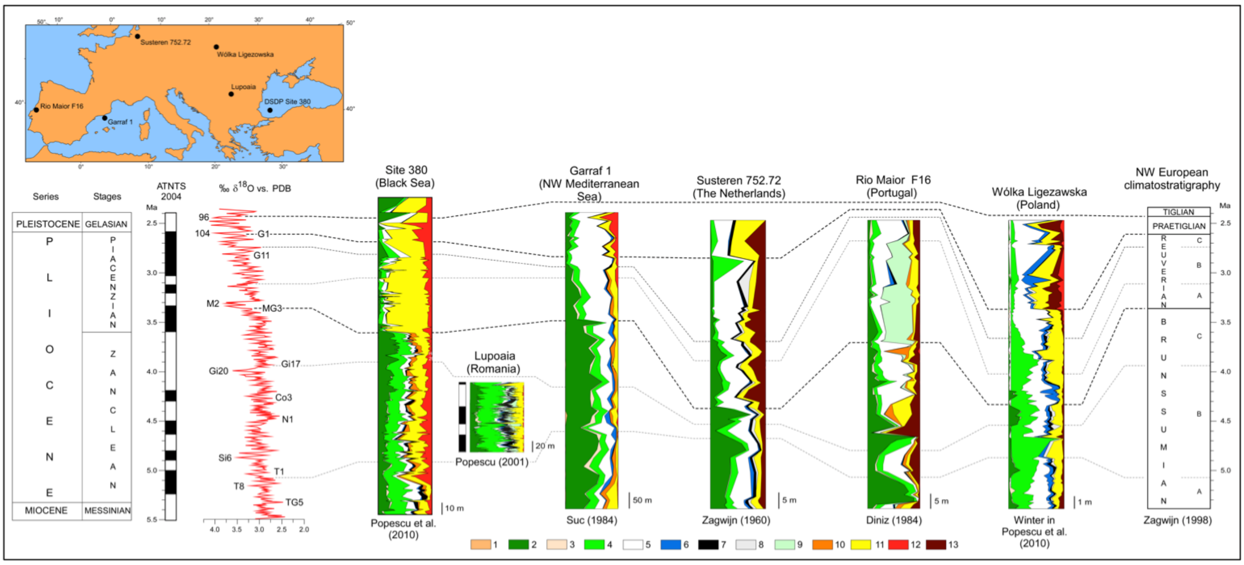

Fig. 1 - Example of climatostratigraphic correlations at the European scale between six long pollen records from the earliest Pliocene to earliest Pleistocene and chronologic calibration of the Northwestern European climatic succession (modified from Popescu et al., 2010). Pollen groups (thermic classification: Nix, 1982): 1, Megathermic elements (*Canthium*, Sapindaceae, *Bombax*, etc.); 2, Mega-mesothermic elements (*Taxodium*-type, *Sequoia*-type, Arecaceae, *Engelhardia*, *Distylium*, *Microtropis fallax*, etc.); 3, *Cathaya* (= *Pinus* haploxylon-type at Wólka Logezawska); 4, Mesothermic elements (*Quercus*, *Carya*, *Pterocarya*, *Liquidambar*, *Carpinus*, *Ulmus*, *Zelkova*, etc.); 5, *Pinus*; 6, Meso–microthermic trees (*Cedrus*, *Tsuga*, *Keteleeria*); 7, Microthermic trees (*Abies*, *Picea*); 8, Elements of no significance (Ranunculaceae, Rosaceae, etc.); 9, Cupressaceae (*Cupressus*–*Juniperus*-type); 10, Mediterranean xerophytes (*Olea*, *Pistacia*, *Ceratonia*, *Quercus ilex*-type, *Rhamnus*, *Cistus*, etc.); 11, Herbs (Amaranthaceae, Asteraceae, Poaceae, Apiaceae, *Rumex*, Borraginaceae, *Convolvulus*, Cyperaceae, Caryophyllaceae, etc.); 12, Steppe elements (*Artemisia*, *Ephedra*, *Hippophae*); 13, Ericaceae.

Europe (Zagwijn, 1986; Gibbard et al., 1991; Suc et al., 1995; Pontini & Bertini, 2000; Bertini, 2001; Popescu et al., 2010) (Fig. 1). In addition his work provided a firm foundation for reconstructing the evolution of the North Sea region throughout the late Cenozoic.

2. THE LOWERING OF THE PLIOCENE–PLEISTOCENE BOUNDARY FROM 1.8 TO 2.58 MA

The age of Praetiglian cooling having been established within the late Pliocene (at that time, the Pliocene extended to 1.8 Ma), the International Commission of Stratigraphy (ICS) approved the creation of a third stage for the Pliocene, the Gelasian (2.6–1.8 Ma), sandwiched between the Piacenzian Stage (3.6–2.6 Ma) and the intact Calabrian Stage (starting at 1.8 Ma) (Rio et al., 1998), aiming to avoid the prospect of lowering the Pliocene–Pleistocene boundary from 1.8 to 2.6 Ma (Suc et al., 1997). However, the Quaternary community consolidated its position and, despite a disappointing setback in 1997 (for full details, see: Head & Gibbard, 2015), succeeded on 29 June 2009 in obtaining formal ratification from the executive committee of the IUGS to lower the Pliocene–Pleistocene boundary to the base of the Gelasian Stage with an age of 2.58 Ma (Gibbard & Head, 2010; Gibbard et al., 2010) (Fig. 2).

Waldo H. Zagwijn was a strong and vocal advocate of a Pliocene–Pleistocene (and Neogene–Quaternary) boundary that coincided with the base of the Praetiglian, and he readily offered arguments in support of this view, whether to opponents or supporters. Zagwijn was also convinced that Quaternary time

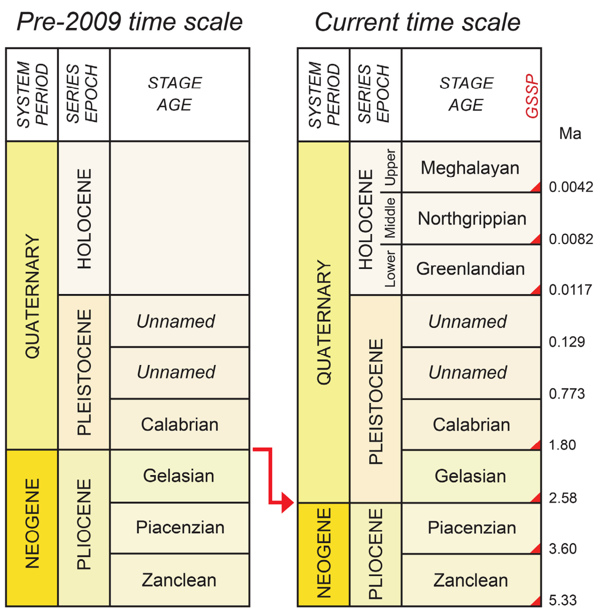

Fig. 2 - The geological time scale as it existed before the base of the Pleistocene was lowered to that of the Gelasian in 2009, and the current IUGS/ICS geological time scale. [IUGS/ICS geological time scale.]

was distinct and that it should not be incorporated into the Neogene (Fig. 2), as some of his countrymen had advocated for several decades. There can be no question that, at the age of 81, he felt this IUGS decision to

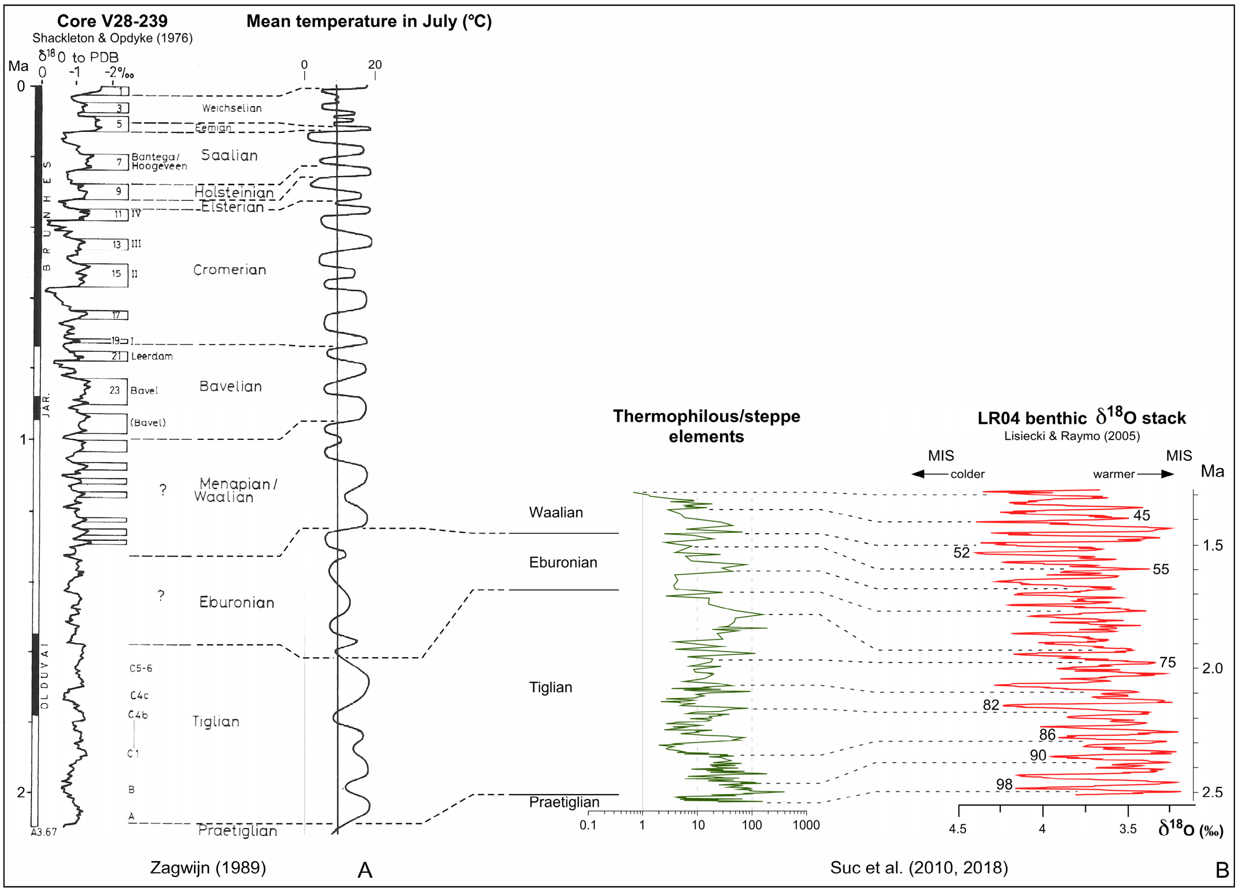

Fig. 3 - Climatic curves resulting from pollen records compared to oxygen isotope curves. A) The Netherlands climatic curve matched to an oxygen isotope curve (modified from Zagwijn, 1989); B) Focus on the latest Praetiglian to early Waalian pollen ratio 'thermophilous/steppe elements' from the Mediterranean region (Crotone, Calabrian Stage) compared with the LR04 benthic $\delta^{18}O$ stack (modified from Suc et al., 2010, 2018).

be the ultimate recognition of his work. This was not only a vindication of his concept but an acknowledgement that climate (and of course palynology) should play a prominent role in formal stratigraphy, at least for the Quaternary.

3. EXTENDING THE NUMBER OF GLACIAL–INTERGLACIAL CYCLES, AND DRAWING PALYNOLOGY CLOSER TO ISOTOPE STRATIGRAPHY

After defining how respectively to characterise glacials and interglacials by pollen assemblages and then delimit them (Zagwijn, 1957), Zagwijn (1960) proposed a climatic subdivision of the Pleistocene of The Netherlands that has been continuously refined to this day by the discovery of new phases (Zagwijn, 1989, 1998; Fig. 2A) extendable over the entire southern North Basin (Gibbard et al., 1991). This evolution is explained by the discontinuous character of sedimentation in the delta to flood-plain environmental contexts in which Zagwijn worked. Integration was achieved by piecing together sequences based on the integration of multidisciplinary litho- and biostratigraphical investigations from across the country (Zagwijn & Doppert, 1978; Zagwijn, 1989). Keen to compare his pollen data with oxygen isotope records, Zagwijn (1985) constructed a curve of estimated summer (July) mean temperatures in The Netherlands from pollen-analytical data, and data on cryoturbatic structures (Fig. 2A; for details, see: Zagwijn, 1985). Zagwijn's curve was validated as representative of climatic megacycles by Kukla & Cílek (1996).

Condensing pollen data into a single curve is a crucial challenge because the progressive enrichment of pollen floras by many new taxa over time complicates interpretation. In the Mediterranean region, where temperature and precipitation critically combine to characterise climate change, a pollen index is displayed by the ratio of 'thermophilous plants/steppe elements', which provides a curve directly comparable to oxygen isotope records (Fig. 3B; Suc et al., 2010). The curves illustrate the great variability of climate during each phase of a megacycle as shown for the Tiglian and Eburonian stages (Fig. 3B). For example, the Praetiglian as characterised by W.H. Zagwijn with few or no minor subdivisions, has progressively been shown to abound in secondary climatic fluctuations (Suc, 1984; Pontini & Bertini, 2000; Bertini, 2001; Donders et al., 2018) and may have a complex lateral expression owing to local palaeoenvironmental variation (Donders et al., 2007). Following the path well trodden in The Netherlands, sustained effort

Fig. 4 - Waldo H. Zagwijn (to the right) receiving the Penck Medal in 1973, photographed by the organizer.

has been directed at collecting new pollen data and synthesizing with existing records in the Mediterranean region to enhance our understanding of vegetational and climatic evolution (Suc & Popescu, 2005; Leroy, 2007; Bertini, 2010; Popescu et al., 2010; Combourieu-Nebout et al., 2015; Suc et al., 2018). Finally, pollen transfer functions are now being used to reconstruct past climate from locations across Europe (Fauquette et al., 2007).

4. AN IMPRESSIVE PERSON AND A BRILLIANT CAREER

Anyone who has known Waldo Zagwijn remembers his humility and constant attention to others. His intelligence shone through his sparkling eyes. Always affable and imbued with a keen sense of detail, Zagwijn was immensely interested in training young geologists and palynologists as illustrated by his commitment as a Professor at the Free University Amsterdam.

Well into retirement, Waldo H. Zagwijn remained keenly interested in biology and geology, traits that guided his eminent career at the Geological Survey of The Netherlands. Crowned with numerous distinctions including Life Fellowship of INQUA, royal appointment as an officer of the Order of Orange-Nassau, and recipient of the Penck Medal (Fig. 4), he was elected in 1980 as a member of the Royal Academy of Sciences of The Netherlands (*Koninklijke Nederlandse Akademie van Wetenschappen*). On the occasion of his retirement, the Accademy celebrated his life's work on October 1993 with an international symposium and a volume including his complete bibliography and many dedicated papers (Herngreen & van der Valk, 1995).

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