

Marine tephrochronology: a personal perspective

DAVID J. LOWE^{1,2}

¹*School of Science, Faculty of Science and Engineering, University of Waikato, Private Bag 3105, Hamilton, New Zealand 3240*

(e-mail: d.lowe@waikato.ac.nz)

²*President, International Focus Group on Tephrochronology and Volcanism (INTAV), Hamilton, New Zealand*

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Introduction

This special volume on marine tephrochronology is remarkable, and timely, because it marks a concerted step towards what might be informally termed 'phase 3' of a revolution in Quaternary geosciences that began around 40 years ago. The ten articles collectively represent a re-focussed examination of tephras and cryptotephras preserved in ocean sediments at various locations and the authors describe their significance for a range of subdisciplines. Eight provide a new understanding of the origin, distribution, and ages of various tephra and cryptotephra deposits and their stratigraphic inter-relationships; how the terrestrial ages of the tephra/cryptotephra deposits relate to those of enclosing sediments and inform the ongoing development of the marine radiocarbon time-scale; mechanisms for the emplacement, remobilisation, or bioturbation of the tephras or cryptotephras; and volcanic eruption history. Two further articles document the characterization of tephra-derived glass shards using microbeam techniques to analyse 30–40 elements from individual shards as small as 10 μm in diameter. The collection thus provides snapshots of many aspects of the latest developments and directions in tephra studies – volcanology, primary and secondary dispersal, stratigraphy, single-grain characterization, chronology – through the medium of marine sediments. My personal perspective reflects briefly on how this point was reached and identifies a few of the important milestones on the way from 'phase 1' to 'phase 3'. I am privileged to write it.

Marine science revolution

As an undergraduate in the early-mid 1970s, I recall my first real ‘awakening’ regarding the *dynamic* nature of science, and of Quaternary geoscience in particular, when told about deep-sea core V28-238 from the equatorial Pacific Ocean (Shackleton & Opdyke 1973) (>2650 citations, Google Scholar). Analogous to the opening notes of Beethoven’s 5th Symphony, perhaps the most famous quartet of notes in history, the alpha-numerical assemblage ‘V28-238’ is possibly the most instantly-recognizable abbreviation in Quaternary science (‘V’ stands for *Vema*, the three-masted coring schooner of the Lamont Geological Observatory, now the Lamont-Doherty Earth Observatory of Columbia University). Lecturers Michael Selby and Cam Nelson (both now retired) at the University of Waikato, New Zealand, strongly emphasised the importance of V28-238, and of the deep-sea marine record in general, in developing a much more comprehensive understanding of changes in the Quaternary than previously attained. Although the modern phase of deep-sea drilling began in the 1950s, the formative findings emerging in the 1970s, including those of Hays *et al.* (1976) (>2800 citations, Google Scholar) have, rightly, been regarded as revolutionary (Walker & Lowe, 2007). At this time, remember, the substantive theory of ‘plate tectonics’ was barely a decade old, and articles were still being published regularly on the correlation of on-land terrace sequences with the so-called ‘four main Pleistocene glacial episodes’. In their discussion on the chronology of V28-238, Shackleton & Opdyke (1973, p. 49) recorded the potential of tephrochronology by commenting on the usefulness of an Italian tephra (a ‘Tuff with Black Pumices’): “If this eruption could be confidently placed in a climatic sequence, it is possible that it could be used to render our chronology even more accurate.”

The sense of discovery and the dramatic new world of possibilities that had opened up with the marine-based research continued in the 1980s when Cam Nelson took part as a ship-board scientist on the *Glomar Challenger* on Leg 90 (December 1982–January 1983) of the Deep-Sea Drilling Project (DSDP) that included coring in both the Tasman Sea and the Pacific Ocean immediately east of New Zealand (Fig. 1) (the final voyage of the *Glomar Challenger*, Leg 96, took place in October, 1983). Although not directly involved, it was exhilarating to be rubbing shoulders with Cam whilst he was working on material from the Leg 90 cores (Fig. 2). Cam and others including Chris Hendy, Paul Froggatt, and Kerry Black soon published several critically important papers, one showing for the first time synchronicity between long-term glacial and interglacial signals of both hemispheres and a ‘genetic link’ between alpine glaciation and the marine isotope record (from analyses of core sediments from the DSDP site 594) (Nelson *et al.* 1985a, 1986), another documenting a new spectral analysis procedure for dating Quaternary deep-sea sediments (Black *et al.* 1988), and several articles on the visible (‘megascopic’) tephra record preserved in the marine sediments (Nelson *et al.* 1985b; Froggatt *et al.* 1986) (Fig. 3). A startling find was that tephra deposits could be markedly thicker ‘upwind’ of source: ash ascending above 20 km altitude was carried directly westward towards the Tasman Sea by easterly stratospheric winds, while coeval lower-level ash was blown eastward (‘downwind’) of New Zealand into the southern Pacific Ocean (Nelson *et al.* 1985b). A second interesting result was the recognition that the visible tephras were only a fragmentary record of Quaternary volcanism in the southwest Pacific because New Zealand-derived silicic shards were a ubiquitous but disseminated minor component in many of the sediments in the cores. The disseminated glass shard concentrations, not visible as layers, today would be called cryptotephras (Lowe & Hunt 2001; Lowe 2011). In addition, pale-green laminae <2 mm thick,

common and conspicuous features in many of the cores examined (Fig. 4A), were inferred to represent diagenetically altered (mainly smectitic) remnant volcanic ash layers (Gardner *et al.* 1985).

This DSDP-based work thus revealed a compelling story about tephras but it was recognised clearly as being incomplete. Subsequent work on marine sediments in the southwest Pacific, which I have loosely denoted ‘phase 2’, expanded the Quaternary marine tephra record through analysis of cores obtained by various ships including the *JOIDES Resolution* (Ocean Drilling Program [ODP] followed by the Integrated ODP [IODP]), the *Roger Revelle* (Scripps Institute of Oceanography), the *Marion Dufresne* (French Polar Institute Paul-Emile Victor), and the New Zealand research vessel *Tangaroa* (e.g. Pillans & Wright 1992; Carter *et al.* 1995, 2002, 2004; Alloway *et al.* 2005; Shane *et al.* 2006; Allan *et al.* 2008). The orbitally tuned chronology for the ODP/IODP cores, ‘calibrated’ or tested by numerical ages on tephras and magnetostratigraphy, provides an important framework for associated paleoenvironmental reconstructions (e.g. Carter 2005; Naish 2005; Holt *et al.* 2010; Alloway *et al.* 2013) (Fig. 4B). Tephras preserved in marine sedimentary sequences on land were also examined (e.g. Alloway *et al.* 1993; Naish *et al.* 1996; Shane *et al.* 1998; Pillans *et al.* 2005).

Phase 3 – delving into marine cryptotephras in the southwest Pacific region – has barely begun, as noted by Holt *et al.* (2011), although marine records and palaeoceanographic changes in the Australian and New Zealand regions, especially since 30,000 years ago, have now been documented and interpreted in some detail (e.g. Carter *et al.* 2008; Hayward *et al.* 2011; Newnham *et al.* 2012; Bostock *et al.* 2013; Marr *et al.* 2013; Nelson *et al.* 2013).

Hence the work reported in this volume by Austin *et al.* (2014) on sediments in oceans of the Northern Hemisphere is at the forefront of marine tephra studies, and the authors and editors deserve credit and acclaim.

Tephrochronological advances

While the new tephra and palaeoenvironmental work in the marine realm was buzzing in the 1970s and 1980s, complementary advances were taking place on land in the discipline of physical volcanology, especially relating to explosive volcanism and its products (e.g. Walker 1973, 1983; Self & Sparks 1981; Fisher & Schminke 1984; Wilson & Walker 1985; Wilson 1986, 1993), and in the thriving discipline of tephrochronology (e.g. Topping & Kohn 1973; Westgate & Fulton 1975; Machida & Arai 1978; Smalley 1980; Lowe 1990). As well as studies on distal tephra deposits preserved in sediments, and in soils or palaeosols, new laboratory methods for characterizing the glass-shard and crystal (mineral) components of tephra deposits were being developed in a period of substantial technical advancement (e.g. Kohn 1970; Sarna-Wojcicki 1976; Westgate & Gorton 1981; Beaudoin & King 1986). These methods included the innovative use of the electron microprobe, developed mainly through the 1970s and 1980s, to obtain major element compositions of individual glass shards rather than bulk samples (Smith & Westgate 1968; Froggatt 1983, 1992; Hunt & Hill 1996). Its advent in 1968 a stroke of brilliance, the microprobe method for glass analysis, initially criticised by some ‘traditional’ volcanic petrologists and geo-analysts, has been widely adopted today as the cornerstone analytical technique in tephra studies used alongside stratigraphic, chronological, and mineralogical data to help enable correlations to be made (Froese *et al.* 2008a; Lowe 2011). More recent refinements of the electron microprobe

method for the analysis of glass shards or melt inclusions, or for crystals, include those described by Turney *et al.* (2004), Kuehn *et al.* (2011), Matsu'ura *et al.* (2011, 2012), Hayward (2012), Hall & Hayward (2014), Marcaida *et al.* (2014), and Pearce *et al.* (2014). Subsequently, from the mid-1990s, the development of the laser-ablation inductively coupled plasma-mass spectrometric method for the analysis of trace elements in individual glass shards provided another dramatic leap forward in tephra analysis, especially those involving thin distal deposits or cryptotephra (e.g. Westgate *et al.* 1994, 2013a; Pearce *et al.* 2004, 2007, 2011; Tomlinson *et al.* 2010; Preece *et al.* 2011).

Alongside these methods of characterization, new or improved methods for dating tephra or cryptotephra have emerged, such as the isothermal plateau fission-track method for dating glass shards (Westgate 1989; Sandhu & Westgate 1995; Westgate *et al.* 2013b). New ways of developing age models for tephra layers or cryptotephra deposits in sedimentary sequences using wiggle-matching or Bayesian statistical procedures (Buck *et al.* 2003) alongside radiocarbon, optical, $^{40}\text{Ar}/^{39}\text{Ar}$, or other dating methods have become very important as well in the past decade (e.g. Hogg *et al.* 2003, 2012; J. Lowe *et al.* 2007; Lowe *et al.* 2013; Blockley *et al.* 2008; Blaauw & Christen 2011; Biswas *et al.* 2013; Smith *et al.* 2013). Methods by which tephra or cryptotephra could be correlated on a more quantitative basis using numerical or statistical analysis of their compositional data, along with other information such as stratigraphic position and relationship to other tephra or deposits, palaeoecological or archaeological associations, and numerical age, are currently being reviewed and evaluated.

Perhaps the most unexpected development during my career has been the flourishing of tephra studies in areas remote from volcanic sources through cryptotephra deposits (Lowe 2008). The rise of a new generation of cryptotephra specialists all around the

world has been astounding. Given that my own early New Zealand work was on distal tephras, including studies on admixed 'non visible' tephras in buried soil sequences (e.g. Lowe 1986), I should perhaps have been more prescient! The advent of *systematic* studies of cryptotephras – the identification, correlation, mapping, and dating of sparse, fine-grained glass-shard and/or crystal concentrations 'hidden' within sediments or soil – over the past 25 years since Andrew Dugmore's seminal (1989) paper has undoubtedly been revolutionary. Although new and increasingly efficacious techniques for cryptotephra detection, extraction, and identification were developed primarily in northwestern Europe and Scandinavia, and more lately North America (e.g. Turney 1998; Dugmore *et al.* 1992, 1995; Wastegård *et al.* 2000; Hall & Pilcher 2002; Blockley *et al.* 2005; Gehrels *et al.* 2008; Payne *et al.* 2008; Kuehn & Froese 2010; Pyne-O'Donnell *et al.* 2012), earlier work in New Zealand had demonstrated the occurrence of glass shards or crystals in concentrations not visible as layers in sedimentary deposits or soils. Robertson & Mew (1982) were the first to count glass shards in soils developed on loess and glacial deposits in western South Island, writing (p. 506) ... "Although no distinct ash layers were observed in the West Coast soil profiles, it is probable that, as the amounts of glass present are low, such a layer would be difficult to detect in the field". The shards were subsequently identified as correlatives of the c. 25,400 cal. year-old Kawakawa tephra; 'cryptic' occurrences in loess elsewhere were also identified through glass-shard counting and major element analysis (Mew *et al.* 1986; Eden & Froggatt 1988; Almond 1996; Vandergoes *et al.* 2013). Lowe *et al.* (1981) and Lowe (1988a) were among the first to use X-radiography to detect non-visible glass shard concentrations in peat and lake sediments and to characterize them using a rapid X-ray fluorescence technique, and Hogg & McCraw (1983, p. 182) used the sparse occurrence of distinct (optically dark green) aegirine crystals in ash-derived soils and palaeosols to map c.

7000 cal. year-old Tuhua tephra at least 80 km beyond its visible limits in the field (see also Table 2 in Lowe *et al.* 2008, p. 101).

The burgeoning cryptotephra methods, likened to ‘forensic tephrochronology’, have now been applied to terrestrial, ice-core, and marine sedimentary sequences in all parts of the world (e.g. see Table 1 in Lowe 2008, p. 315). Cryptotephrae have been discovered in peat, lake, marine, and aeolian sediments (including frozen sediment, i.e. permafrost), in ice, in soils and palaeosols, and in deposits in caves. The tenacious cryptotephra studies, although not without serious limitations and problems such as taphonomic issues and quantitation uncertainties (especially when dealing with limited numbers of shards or crystals) (e.g. Payne *et al.* 2005; Davies *et al.* 2007; Lowe 2011; Pyne-O’Donnell 2011; Lane *et al.* 2014), have documented tephra-fall occurrences at sub-millimetre scale at distances spanning hundreds to thousands of kilometres (now described as ‘ultra-distal’), greatly extending known geographical limits to >7000 km from source (e.g. Gehrels *et al.* 2006; Davies *et al.* 2008; Brendryen *et al.* 2010; Lawson *et al.* 2012; Pyne-O’Donnell *et al.* 2012; Lane *et al.* 2013).

Marine cryptotephrochronology: the next revelatory revolution

Returning to the main theme of this volume, the value of marine sediments in providing potentially very detailed records of tephra layers or cryptotephrae, and their applications tephrochronologically, are now well recognised and exploited (e.g. Chun *et al.* 2007; Hillenbrand *et al.* 2008; Abbott *et al.* 2011, 2013; Cage *et al.* 2011; Albert *et al.* 2012; Gudmundsdóttir *et al.* 2012). As recognised by Nelson *et al.* (1985b), cores of marine sediment have the potential to provide a detailed stratigraphic record of tephra fallout

because large proportions of volcanic eruptives are deposited in the sea (Cassidy *et al.* 2013). Together with terrestrial records such as those from lakes, bogs, and ice cores, the marine tephra or cryptotephra deposits can therefore help document patterns of explosive volcanism in time and space, often more comprehensively than those obtainable near volcanic eruption centres, and integrate the stratigraphic interfingering of eruptives from multiple volcanic sources (Lowe 1988b; Alloway *et al.* 2005; Shane 2005; Shane *et al.* 2006; Bourne *et al.* 2010, 2013; Davies *et al.* 2010; Lim *et al.* 2013; Ponomareva *et al.* 2013; Insinga *et al.* 2014).

Although distal deposits tend to be more restricted compositionally than their proximal counterparts generated from the same eruptive episode (e.g. Smith *et al.* 2005), recent work on magmatic heterogeneity at some volcanoes has shown that multiple fingerprints may arise according to tephra dispersal direction during a 'single' eruption episode, adding complexity and the need for a careful approach in making long-range correlations (Shane *et al.* 2008). Potential complications and, paradoxically, insights, thus abound especially in studying tephras and cryptotephras in the marine realm where reworking and bioturbation may be commonplace, and where 'anomalous' grain-size patterns may tell an unexpected story (e.g. Hunt *et al.* 1995; Lackschewitz & Wallrabe-Adams 1997; Lacasse *et al.* 1998; Manville & Wilson 2004; Ascough *et al.* 2005; Kristjánssdóttir *et al.* 2007; Todd *et al.* 2014).

Tephra studies globally are in an incredibly expansive and productive phase right now (e.g. Froese *et al.* 2008b; Lowe *et al.* 2011; Alloway *et al.* 2013; Gorbarenko *et al.* 2013; Smith 2013), with a number of specialist lab groups around the world leading the way in exemplary fashion. Tephra specialists (tephrochronologists) provide essential expertise in numerous projects where tephras or cryptotephras, commonly both, are key stratigraphic

correlational, synchronizational, or dating tools to help meet the objectives of high-resolution palaeoclimatic projects such as INTIMATE (Integration of ice-core, marine and terrestrial records to reconstruct past abrupt and extreme climate changes from 60,000 to 8000 years ago), SMART (Synchronising marine and ice-core records using tephrochronology), CELL50K (Calibrating environmental leads and lags over the last 50,000 years), TRACE (Tephra constraints on rapid climatic events), the Lake Suigetsu 2006 varved sediment-core project (Japan), and SHAPE (Southern Hemisphere assessment of palaeoenvironments). These and other projects (such as the RESET, Response of humans to abrupt environmental transitions), all involving tephrochronology, are meeting the challenge laid down for Quaternary scientists by Walker and Lowe (2007, p. 1087) “to generate integrated datasets of the highest possible quality and temporal resolution to provide meaningful baselines for predictive models of the global future.” Tephra and cryptotephra are also being identified and utilized in growing archaeological and palaeoanthropological studies (e.g. Wastegård & Davies 2009; Housley *et al.* 2012; J. Lowe *et al.* 2012; Streeter *et al.* 2012; Riede & Thastrup 2013; Lane *et al.* 2014).

Conclusion

This benchmark volume sets the scene for the development of the next phase of integrating marine science studies with tephrochronology. Tephra or cryptotephra deposits, usually in the form of glass shard concentrations at distal or ultra-distal sites, provide a chronostratigraphic link to equivalent deposits in other environments including the superlative ice-core records (e.g. Davies *et al.* 2008, 2010, 2014). Such work is already proving to be as stimulating as the breathtaking revelations ‘hailed up’ from the deep

oceans ~40 years ago that helped to inspire several generations of Quaternary geoscientists, myself included.

It is perhaps instructive here to quote from a clever, insightful short essay by Schwartz (2008) on the need to seek answers by asking the right questions through what he termed 'productive stupidity' (p. 1171): "Productive stupidity means being ignorant by choice. Focusing on important questions puts us in the awkward position of being ignorant" and hence "The more comfortable we become with being stupid, the deeper we will wade into the unknown and the more likely we are to make big discoveries."

Always accompanied by the excitement and collegiality of discovery, and lifelong respect and friendship, much is promised and surely will be delivered as we wade deeper into the unknown through marine – and complementary terrestrial – tephrochronology and cryptotephrochronology.

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Fig. 1. The *Glomar Challenger* in Noumea in December, 1982, before embarking on DSDP Leg 90. Photo courtesy of Cam Nelson.



Fig. 2. Cam Nelson (right) inspecting fresh cores with a colleague on *Glomar Challenger* in January, 1983, during the Leg 90 cruise. Photo courtesy of Cam Nelson.



Fig. 3. Micrograph of glass shards of visible tephra no. 13 (after Nelson *et al.* 1985b, p. 1173) from DSDP site 594, subsequently identified by Nelson (1988) as a correlative of the very widespread and voluminous Whakamaru-caldera derived 340,000-year-old Rangitawa tephra (formerly known also as Mt Curl tephra, Ohinewai ash, and Hamilton ash 'H1' bed), which was deposited from a super-eruption near the end of Marine Oxygen Isotope Stage 10 (Kohn *et al.* 1992; Pillans *et al.* 1996; Lowe *et al.* 2001; Holt *et al.* 2010; Matthews *et al.* 2012; Alloway *et al.* 2013). Micrograph courtesy of Cam Nelson (his handwritten notes reflect the pre-digital era).

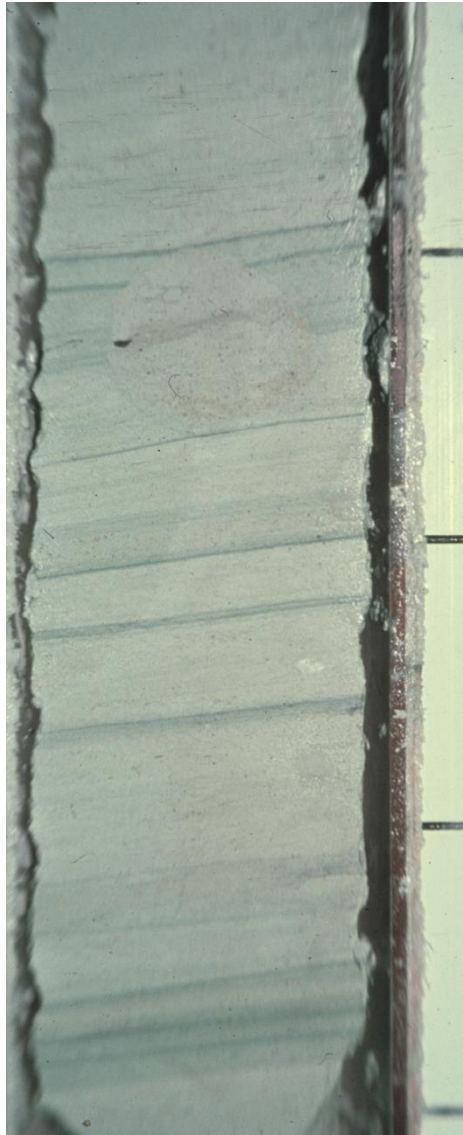


Fig. 4A. Around 12 pale-green laminae (thin dark layers, some composites) in part of a core from DSDP site 599 from central Lord Howe Rise, Tasman Sea (from Gardner *et al.* 1985, p. 1147). Core shown is about 20 cm long (scale marks on right at 5-cm intervals). The laminae comprise mainly authigenic smectite and tend to occur in association with iron sulphide. There is a general correspondence between the occurrence of laminae and the presence of volcanic glass in smear slides, hence their identification as diagenetically altered remnant tephra layers (Gardner *et al.* 1985). Indistinct circular feature near top between the first and third laminae (cutting through the second lamina) is an infilled burrow. Photo courtesy of Cam Nelson.

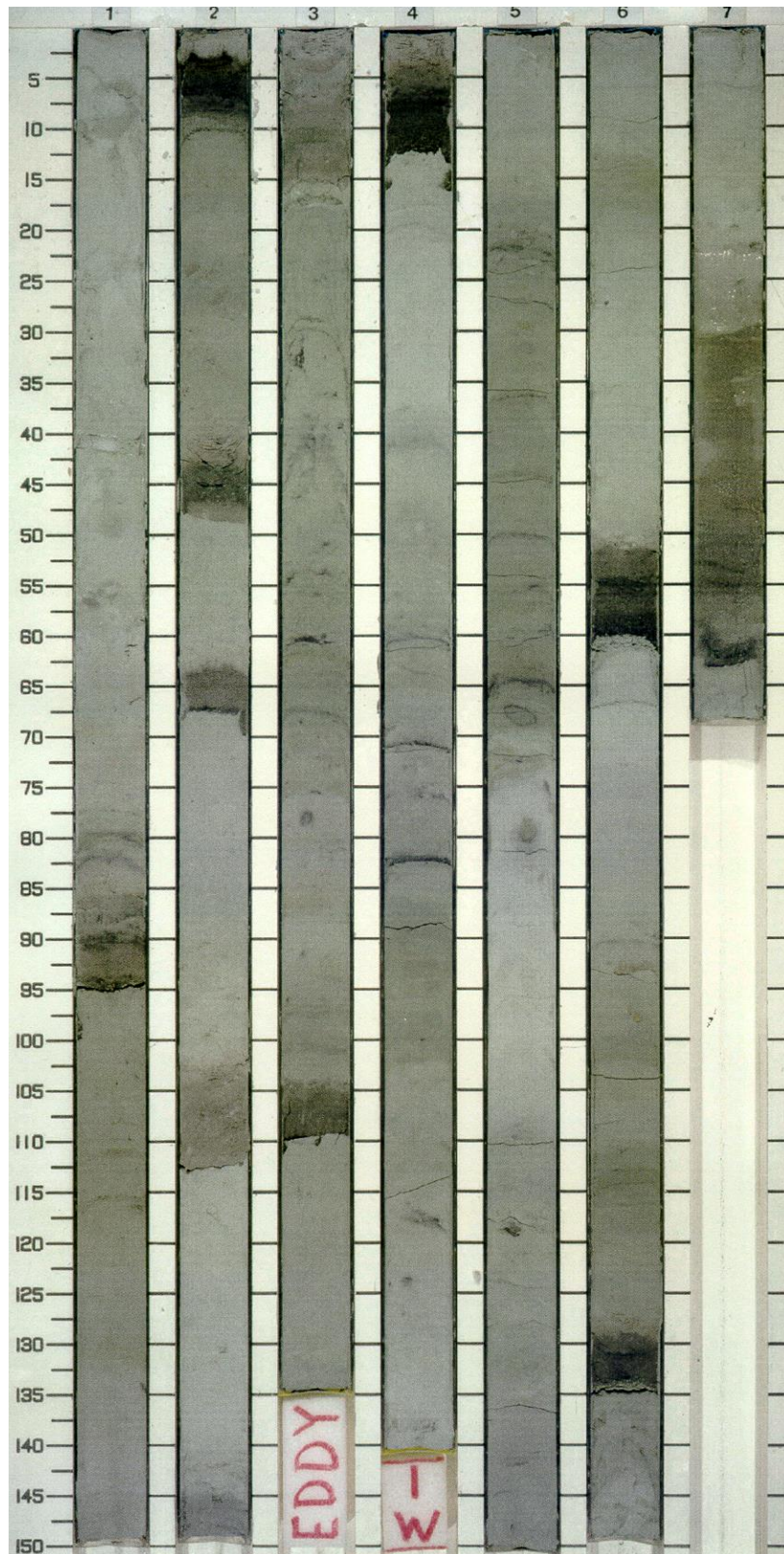


Fig. 4B. Tephra beds (dark coloured) in nanofossil ooze (pale coloured) in cores from ODP site 1124 (~4000 m water depth) due east of central North Island, New Zealand. Scale at left in centimetres. Photo courtesy of Lionel Carter (from Alloway *et al.* 2013, p. 298, with permission from Elsevier).