New Zealand Journal of Geology & Geophysics, 2005, Vol. 48: 623–639
0028–8306/05/4804–623

The status of local "stages" in the New Zealand Pliocene-Pleistocene

R. M. CARTER
Marine Geophysical Laboratory
James Cook University
Townsville, Australia
and
School of Geological and Environmental Science
University of Adelaide
Adelaide, Australia
bob.carter@jcu.edu.au

The best hope for defining the true boundaries through all of the New Zealand Late Neogene is to use radiometric and paleomagnetic dates to calibrate sequences at appropriate places, and thus enable the use of endemic fossils as well as the few useful cosmopolitan ones. (Paul Vella 1975, p. 91)

Abstract Three different systems of nomenclature are in use for New Zealand's Pliocene-Pleistocene rocks: marine stages, glacial stages (and advances), and international chrons and isotope stages based upon magnetic and oxygen isotopic criteria, respectively. The New Zealand marine stages, created by J. Allan Thomson in 1916, have evolved largely as biostratigraphic entities despite their chronostratigraphic appellation, and the scheme remains in active though ambiguous use. Over the last 20 yr, international magnetic and isotopic subdivisions have become widely adopted, driven by the availability of long offshore cores (DSDP Site 594, ODP Sites 1119, 1123), the reinterpretation of classic sections in eastern and western North Island (Mangaopari and Wanganui Basins), and the refinement of tephrochronology and other modern dating methods. One result is that the onland glacial stage scheme is falling into disuse, replaced by marine isotope stage (MIS) terminology. Meanwhile, attempts to provide rigorous definitions for the marine stages via Local Standard Stratotype-section and Point (LSSP) markers have ended in disagreement, with some researchers (e.g., Carter & Naish) favouring the use of objective ash bed or magnetic reversal markers as stage boundaries, and others (e.g., Beu, and Scott) preferring to retain traditional biostratigraphy. A fundamental distinction must be drawn between the definition of stages and their correlation. The errors inherent in the different criteria which are used for these operations in the Pliocene-Pleistocene are discussed. It is recommended (following QMAP practice) that international magnetic reversal and oxygen isotope divisions be used for referring to the age of New Zealand Pliocene-Pleistocene rocks back to 4 Ma, and perhaps beyond to the base of the Pliocene (c. 5.2 Ma). If they are to continue in usage, the local marine stages should have their historical meanings preserved by either: (1) rigorous definition as ages, using LSSP which are based on testable, objective criteria; or (2) reversion to use as biostratigraphic zones (oppelzones), with the implications that they may possess indeterminate ("fuzzy") boundaries and have different age spans in different places.

Keywords stratigraphic classification; age; stage; oppelzone; Pliocene-Pleistocene

INTRODUCTION

Unsatisfactorily, there are presently three different systems of nomenclature in use in New Zealand Quaternary stratigraphy, namely: local marine stages, local glacial stages, and international terminology. The glacial stages are used mainly for the mapping and interpretation of glacier-proximal, non-marine sediments, and, by general agreement, are rapidly being supplanted by international marine isotope stage terminology (see discussion in Carter 2005). In contrast, sharp disagreements exist over the ways in which the New Zealand marine stage classification should be interpreted (see Carter & Naish 1998; Beu 2001; Scott 2001). Meanwhile, the real world is passing us by, for the oxygen isotope stages of Emiliani (1966), Shackleton & Opdyke (1973, 1976), Shackleton et al. (1990), and Tiedemann et al. (1994) long ago became the de facto basis for worldwide stratigraphic subdivision of the Pliocene-Pleistocene.

This paper examines why some of the suggestions regarding New Zealand Pliocene-Pleistocene classification made by Beu (2001) and Scott (2001) are untenable insofar as they relate to traditional *time-scale* issues, as opposed to biostratigraphy, and why the best course of action is the adoption back to at least 4.0 Ma of the global oxygen isotope record for time-scale use in New Zealand. If, at the same time, some stratigraphers wish to persist with the parallel use of local stage names, then it becomes important that redefinitions of stage boundaries be minimised in order to preserve the earlier information content of traditional names.

Note on terminology

The term **biostratigraphic** is used in this paper in the Hedberg (1976) sense of a body of strata from which one or more requisite fossil taxa have been collected. The main biostratigraphic units are **biozones** of various types, which are concrete entities characterised by their fossil content. Walsh (1998, 2005a) and Walsh et al. (2004) have recognised also **biochronologic** and **biochronostratigraphic** units, which correspond, respectively, to the span of time during which a

G04028; Online publication date 10 October 2005
Received 18 July 2004; accepted 15 August 2005

specified taxon lived and the corresponding strata deposited during that span of time. Despite the "bio" prefix, such units are chronostratigraphic rather than biostratigraphic in nature. Post hoc, many users of the New Zealand regional stages can be inferred to have attributed a biochronologic or biochronostratigraphic meaning to them, despite the historical roots of such "stages" as biostratigraphic units (biozones of the oppelzone category; Carter 1974).

Many other regional stratigraphic "stage" schemes, similarly, can be inferred to be made up of de facto biochronologic/biochronostratigraphic units. This led Walsh (2001, 2003) to suggest that legitimate chronologic/chronostratigraphic units could be of three types: (1) rigidly-GSSP-delimited units; (2) flexible biochronologic units; and (3) numerically delimited units (as in current use in the Precambrian). Walsh (2005a) would classify the New Zealand units within his category 2 biochronologic units, and thus allow them to be referred to as ages/stages (Walsh 2005b). Such a proposal has pragmatic strengths, but overall the practice would exacerbate the semantic confusion which already surrounds many local or regional stage schemes.

Hereafter, when discussing the distribution of fossil taxa within SSP or other sections, the terms Lowest Occurrence (LO) and Highest Occurrence (HO) are used, in the sense of Walsh (2000).

THE NATURE OF THE NEW ZEALAND MARINE STAGES

In introducing his local stage classification for the New Zealand Cenozoic, Thomson (1916, p. 29) remarked that he was introducing "a series of stage names corresponding to all the divisions of geological time represented in our rocks". He was followed in that ambition by most later New Zealand writers, and specifically by Allan (1933) and by Finlay & Marwick (1940, 1947) in the influential papers in which they added new stages and details to Thomson's original listing. Despite this intent to erect *time* units, until recently it has been non-controversial that the stages are actually biostratigraphic units. Scott (1965) stressed their empirical homotaxial nature, whereas Carter (1970, 1974) viewed them as oppelzones in the sense later formalised in Hedberg (1976). These niceties notwithstanding, by far the majority usage of the local New Zealand stages has been in the context of communicating the age of different strata, that is, de facto they were (and are to this day) used as ages rather than as stages or biozones. This intent is made completely clear by publications such as the revised New Zealand time-scale (and "stages") of Morgans et al. (1996) and its recent successors (GNS 2003; Cooper 2004).

It has remained problematic, therefore, that although type localities were generally designated for New Zealand marine stages at the time of their introduction, the stage boundaries at the type localities were often unclear, leading to uncertainty as to a stage's time span, including the possibility of gaps or overlaps between them. This longstanding problem led Fleming (1953, p. 102), for instance, to suggest that the stages might best be characterised by recognising a "typical" fauna for each, and allowing fuzzy boundaries or transitions to be recognised between contiguous stages. Another solution, that of discarding stages judged to be redundant because they substantially overlapped with others, was adopted by Scott (1972).

Thomson introduced the local New Zealand stages in 1916, at a time before a clear differentiation was drawn between biostratigraphic (fossil), chronostratigraphic (time-rock), and chronologic (time) units (e.g., Schenck & Muller 1941; Hedberg 1972). Thus, which of these three categories Thomson's stages belonged to was simply not an issue at and for some time after their introduction, since they belonged to all three! But, as the protracted argument since the 1950s over the reinterpretation of classical European stages shows (see, e.g., Aubry et al. 1999 and Walsh 2001, 2004), the modification of historic terminology is never easy, and so it has proved too for the New Zealand stages.

The development of modern views

The key step for placing stage terminology on a rigorous footing, and cutting through the maze of special biostratigraphic pleading that surrounds specific issues, was taken by Campbell (1959, and other similar papers). In proposing new stages for the New Zealand Triassic, Campbell clearly modelled his approach on that of Thomson but stressed even more the fundamental importance of distinguishing between the *definition* of a stage, and its (logically) later *correlation*. This distinction established, only the base of each stage was defined by Campbell in its type section, the top being recognised by correlation with the base of the superjacent stage at its own (generally different) type locality. Thus, the Warepan Stage was "defined as those beds laid down at the type locality after the appearance of *Monotis richmodiana* Zittel and before the appearance of an Otapirian fauna". That Campbell's approach was rooted in biostratigraphy does not detract from the principle that he was enunciating, which

---

NOTE ADDED IN PRESS: This paper was completed just prior to publication by the Institute of Geological & Nuclear Sciences (IGNS) of a comprehensive updated version of "The New Zealand Geological Time Scale". This monograph formalises the approach of "defining" the lower boundary of New Zealand local stages by nominating one or more bioevents as a proxy, accompanied in some, but not all, cases by a specified boundary stratotype or reference section (Cooper 2004, table 1.3). For some stages, such as the Kapitean, this leads to three alternative definitions for the base of a unit: that is, LO *Sectipecten wollastoni*; LO *Globoconella conomiozea*; and, after established earlier usage, the base of the Callaghans Greensand. Similarly worrisome, ambiguous Pleistocene stage definitions were manifest in a web predecessor (GNS 2003) to Cooper (2004), and are discussed in more detail later in this paper.

Historically, IGNS (as the former New Zealand Geological Survey) has played the role of "regulator" of New Zealand stratigraphic nomenclature, enforcing preferred schemes by the simple expedient of being the organisation that publishes the geological maps and most of the geological monographs. Changes such as the replacement of Wangaloan by Teurian, and the discarding of the Awamoan Stage and the substages of the Wanganui Series, have all drawn protests from experienced non-Survey geologists, but generally to no avail. The latest suggested stage definitions by GNS appear to have reverted to the much-criticised and obsolete European method of boundary recognition; that is, of designating a boundary using one or more taxa whose stratigraphic range or taxonomic interpretation may in future change, at which time the stage boundary changes also. It seems, therefore, that the time has come for the Geological Society of New Zealand to establish an expert group to receive submissions and make recommendations on changes in New Zealand stratigraphic terminology. If balanced in its composition, such a committee could rapidly resolve the present ambiguities satisfactorily. Certainly, recommendations made by such a committee would carry a greater imprimatur than the current unsatisfactory situation of ex cathedra assertions by individual scientists and organisations.

was that stages should be defined by their bases only, by an objective criterion, and in type sections.

This approach was rediscovered a few years later, apparently independently, by the Stratigraphic Classification Subcommittee of the British Geological Society (George et al. 1967), who proposed the use of basal marker points for subdivisions of the standard stratigraphical scale. The baton was then taken up by the International Subcommission on Stratigraphic Classification and evolved rapidly into the concept of defining units by the insertion of Global Standard Stratotype-section and Point markers (GSSP; "golden pegs"). Since 1977 (McLaren 1977), GSSPs have been in the process of implementation for the redefinition of all periods/systems of the geological time-scale (Remane et al. 1996; Ogg 2003) and, beyond that, ages/stages (Gradstein et al. 2004). Where analogous markers are inserted to underpin a parallel local time-scale, they are conveniently termed Local Standard Stratotype-section and Point (LSSP) markers.

International GSSPs draw their legitimacy from the formal ratification which follows only after a long process of consultation and discussion amongst many different expert stratigraphers. Though LSSPs are similarly intended to create stability in stratigraphic nomenclature and usage, they generally only have immediate status in the eyes of those who propose them. The test of the value of competing LSSP designations, therefore, has to be their usefulness as determined by subsequent usage over a substantial period of time.

ERRORS IN AGE DETERMINATION

Until the 1970s, the local biostratigraphic stages, with their known inadequacies (e.g., Boreham 1963; Beu 1969), were the main means of correlation of late Cenozoic strata in New Zealand. Improvements in correlation accuracy since then have come not only from more refined biostratigraphic studies (e.g., Hornibrook 1976, 1980; Scott et al. 1990; Beu 1995), but especially from novel techniques such as tephrochronology (Seward 1976; Alloway et al. 1993; Shane et al. 1995), magnetostratigraphy (Turner & Kamp 1990; Pillans et al. 1994), and cyclostratigraphy (Abbott & Carter 1994; Naish et al. 1996; Naish & Kamp 1997; Saul et al. 1999). Each of these techniques has its own particular type of error, as does biostratigraphy. Not all such errors can be quantified easily, but an understanding of their general type and magnitude, as outlined below, is nonetheless useful. Numeric dating techniques which are mainly relevant to the shorter time-scales within the last glacial cycle (MIS 1–5) include thermoluminescence, amino acid racemisation, and cosmogenic isotope measurement (including radiocarbon), and are not included in the discussion which deals mainly with sediments older than c. 125 ka.

Analytical errors

Numeric estimates of age in the Pliocene-Pleistocene are mostly based on isotope (e.g., $^{40}Ar/^{39}Ar$) or fission-track decay counts, the results of which are used in an age-algorithm calculation which also incorporates the decay-constant for the element in question. Errors in this process include random sampling variations, instrumental noise, and the accuracy with which the decay constant is known. The first two of these processes affect the precision of replicate age determinations and are included within the quoted standard deviation error, which with best practice can be reduced to c. 1% of the sample age (Geyh & Schleicher 1990); operator error may be much larger. Assuming an accurate decay-constant, uncertainties of c. 30–150 k.y. are therefore characteristic of even the best determined Pleistocene numeric ages (e.g., Pillans et al. 1996), and increase to several hundred thousand years in the Pliocene.

Sampling errors for biostratigraphic LOs and HOs

The range of biostratigraphic index fossils is generally judged from their presence or absence in a contiguous series of discrete outcrop or core samples. For example, microfossil samples during ODP drilling legs are taken routinely from the core-catcher interval of each successive core drilled (i.e., are spaced at c. 10 m stratigraphic intervals). For a biopelagic ooze accumulating at, say, 2 cm/k.y., this leads to an uncertainty of up to –500 or +500 k.y. for a determined biostratigraphic LO or HO, respectively. For cores through nearer shore terrigenous facies, which have sedimentation rates between 100 and 10 cm/k.y., lower sampling uncertainties of 10–100 k.y. apply, respectively. Onland studies of the common New Zealand Pliocene-Pleistocene siltstone facies (e.g., Hornibrook 1976) typically fall within this error range also.

Magnetic reversal error

The age of late Cenozoic magnetic reversals is determined both by direct numeric dating and more accurately from outcrops (Lourens et al. 1996) or cores (Shackleton et al. 1990; Tiedemann et al. 1994) with astronomically tuned marine isotope records. For reversal boundaries back to 5.2 Ma the estimated error ranges between 1 and 23 k.y. (av., 9 k.y.) (Lourens et al. 1996). Such accuracy is, however, rarely attainable in practice. First, transitions between magnetic states do not occur instantaneously, but occur over time periods of a few hundred to a few thousand years (e.g., Prevot et al. 1985). Second, and even as the reversal occurs, there is an inevitable magnetic "recording" error which reflects uncertainties associated with the process of magnetic remanence acquisition (e.g., Roberts & Turner 1993). And a third source of error, which is difficult to specify quantitatively, stems from the laboratory magnetic cleaning that is sometimes necessary to reveal the primary remanence signal. Taking all these factors into account, the realistic "geological" error associated with an outcrop reversal boundary might be closer to 100 k.y. than to 9 k.y.

Misidentification errors

Errors which stem from operator misjudgement are difficult to characterise systematically, for they are method-dependent and may be indiscriminately small or large. For example, for *tephrochronology,* the misidentification of a numerically dated ash might result in a small error of 10 k.y. within a succession of many closely spaced ashes, or a larger error of, say, 100 k.y. or more where ashes are spaced farther apart. For *magnetic reversal stratigraphy*, attribution of a wrong polarity interval usually occurs only if other criteria (i.e., biostratigraphy) are inadequate as guides. When such misattributions occur, however, the age error is usually substantial (i.e., many hundreds of thousands of years or more). For example, a reverse to normal polarity transition in the Rangitikei valley documented by Seward (1974) was interpreted as the Brunhes/Matuyama boundary. Pillans et al. (1994) later confirmed the transition, but interpreted it as the middle Matuyama/Jaramillo boundary, a difference (error) of c. 300 k.y.

In contrast, and because of the well-described and understood nature of the New Zealand late Cenozoic molluscan fauna (e.g., Beu & Maxwell 1990; Beu 1995), *macropaleontologic* misidentification is rarely a significant issue.

In contrast again, species discrimination in *micropaleontology* is often subtle. Significant differences therefore may occur between different operators with respect to taxon recognition and consequently in estimated stratigraphic ranges, especially in nannofossils and planktonic foraminifera. For example, the usefulness of gephyrocapsids in Pleistocene stratigraphy has been greatly improved since the general adoption of the rigorously separated small (<3.5 μm), medium (3.5–5.5 μm), and large (>5.5 μm) size categories (Rio 1982; Raffi et al. 1993). However, many nannofossil and microfossil taxa are not separated according to similarly rigorous criteria. A conservative estimate of the error in microfossil identification between different operators might therefore be in the order of 100 k.y.

Homotaxial asynchrony

As Scott (1965, 2001) has long stressed, until recently New Zealand Cenozoic stages were only able to be tested for the homotaxy of their index fossils. At one extreme, homotaxy of a taxon between two different sections may indicate synchrony (e.g., Hays & Shackleton 1976; Thierstein et al. 1977). At the other extreme, a homotaxial event may differ in age by a million years or more between two sections (e.g., *Zygochlamys delicatula*; Beu 1969; Carter 2005). For most late Cenozoic index fossils, including pelagic ones, homotaxial asynchrony is caused by some combination of (1) time transgressive evolutionary appearance or extinction of the taxon in question, (2) facies differences between different sections, and (3) geographic propogation of paleo-water mass or circulation changes. In general, the longer any homotaxial asynchrony is for a particular index fossil, the more likely that other age indicators will signal the problem. Homotaxial age errors in taxa that are today still used as late Cenozoic index fossils are therefore probably most commonly <500 k.y. in length (cf. Carter 2005, table 1). For an example, both the HO of *Cibicides molestus* and the LO of dextral *Globorotalia crassaformis* have been used as indicators for the base-Mangapanian Substage. Yet the *crassaformis* event occurs just before the *molestus* event at Mangaopari Stream (Shane et al. 1995), whereas the reverse is true in the Wanganui Basin (Journeaux et al. 1996). The correlation error associated with this inconsistency is c. 350 k.y.

Cyclostratigraphic errors

Cyclostratigraphic dating of Pliocene-Pleistocene sediments first became possible following (1) the delineation of complete oceanic oxygen isotope curves for the last several million years (e.g., Raymo et al. 1989; Ruddiman et al. 1989), and (2) refined studies of cyclothemic deep-water sediments from the type areas for the Pliocene and Pleistocene in southern Italy and Sicily (e.g., Hilgen 1987, 1991). The astronomical control of deposition of these successions was able to be linked convincingly to the Milankovitch periodicities of Earth's orbit (e.g., Berger & Loutre 1991) and the cyclic successions thereby "tuned" to an astrochronometric age scale (e.g., Shackleton et al. 1990; Tiedemann et al. 1994; Lourens et al. 1996). Following this, it has become routine for marine studies to achieve accuracies of correlation within a few thousand years for cores from different ocean basins back to at least MIS 100 (2.53 Ma), and often beyond. In one of the few comparisons of the accuracy of various dating methods, and as applied to the 345 ka Rangitawa Tephra, Pillans et al. (1996) have shown unequivocally that for multi-dated events the astrochronometrically tuned isotope stage age is superior, and generally accurate to within a few thousand years.

Because of the vagaries associated with sea-level and facies fluctuation during deposition, and the tectonic uplift which results in their exposure on land, emergent Pliocene-Pleistocene successions are not quite so routinely able to be dated to this level of accuracy. However, by the end of the 1990s the unusually complete and well-studied Wanganui Basin succession had been correlated to the marine isotope scale back to MIS 100 (Beu & Edwards 1984; Abbott & Carter 1994; Naish & Kamp 1997; Saul et al. 1999) and beyond (Journeaux et al. 1996; McIntyre & Kamp 1998). These correlations are supported by a strong network of interlocking controls which include magnetostratigraphy, numeric dating of tephra, and biostratigraphy. The correlations are unlikely to be in error by more than one 41 k.y. tilt cycle back to c. 1 Ma, or by more than two cycles for the period 1–3 Ma. Errors of 40 or 80 k.y., respectively, are therefore likely for such cyclostratigraphic age estimates in the New Zealand Pliocene-Pleistocene.

Post-depositional alteration errors

Two main errors are associated with post-depositional sediment alteration. The first affects depositional remanent magnetism, and the second aragonitic fossils.

The basement source rocks for Pliocene-Pleistocene sediments in both islands of New Zealand are dominated by metagreywackes with low contents of iron oxides. Detrital sediments therefore often carry a poor, low intensity depositional magnetic signature. At ODP Site 1119, for example, NRM intensities range from only 10^{-2} to 10^{-5} A/m and there is a strong drill-string overprint that was not easily removed by thermal cleaning; demagnetisation studies suggest that the main carrier is a ferrimagnetic iron sulfide (Wilson & Hu in Carter et al. 1999). Studies of similar sediments onland show a dominant presence of sulfide minerals such as pyrrhotite, greigite, or pyrite (Roberts & Turner 1993). These paramagnetic phases are formed by the early diagenetic alteration of iron oxides, whereas the primary depositional remanence mostly resides in rare detrital titanomagnetite grains that have escaped such alteration. Stable remanence signatures associated with the iron sulfide phases may nonetheless be interpretable provided that their diagenetic origin took place shortly after deposition. Similarly complex Fe-bearing mineralogies appear to be widespread in New Zealand, and it has therefore proved difficult to establish an unequivocal reversal history for some important Pliocene-Pleistocene successions, including both DSDP Site 594 and ODP Site 1119. Intepretation errors are therefore inevitable.

The second type of post-depositional error affects fossils, especially those with aragonitic shells. The venerid genus *Eumarcia*, which has its last apparent occurrence in New Zealand in early Pleistocene (Marahauan) sediments at c. 1.68 Ma, serves as an example. Because of its shoreface habitat, *Eumarcia* usually occurs in high porosity sands or coquinas which are particularly prone to post-depositional pore-water flushing, and consequent dissolution of fossils. That *Eumarcia* was affected by such processes is certain, for it occurs only as moulds in early Pleistocene coquinas from Hawkes Bay (Haywick 1990). Errors in a taxon's estimated LO or HO by up to several eustatic cycles (say 120 k.y.) could easily be caused when such processes proceed to full dissolution in uncemented sediments.

A third error of this type is syn-depositional rather than post-depositional, and comprises the water column and seabed dissolution of calcareous or siliceous microfauna. The commonest example of the effect results from the carbonate undersaturation of waters below the carbonate compensation depth, which today lies at c. 4500 m off eastern New Zealand. However, during cold periods such as MIS 2, enhanced dissolution of calcareous microfossils took place at much shallower depths between 1370 and 2730 m off eastern New Zealand (Weaver et al. 1998). Obviously, such dissolution may affect the apparent ranges of taxa preserved in sediments deposited at water depths greater than c. 1500 m. Though few young sediments from such depths are represented on the New Zealand landmass, dissolution may well have occurred in offshore cores such as ODP Site 1123 and there contribute to stratigraphic uncertainty.

Reworking errors

Two common determinants of age—fossils and volcanic ash—are prone to reworking into younger sediments, a process which was particularly common during the repeated transgressions and regressions which characterised cyclothemic shallow marine successions during the Pliocene-Pleistocene (cf. the common listing of *remanie* fossils in Fleming 1953). Two fossil examples are: (1) the presence of late Pliocene taxa in the basal Castlecliffian Butlers Shell Conglomerate (Fleming 1953); (2) the presence of *Sectipecten* in the Hautawan Piripiri Limestone, eastern Wanganui Basin (Carter 1972). The voluminous nature of some Quaternary eruptions in New Zealand produced a blanketing of the landscape and seabed with ash to a degree that reworking into the ensuing sedimentary cycle became highly probable. For example, in Wanganui Basin, the Potaka tephra (MIS 27; 0.99 Ma) is widely reworked into the transgressive part of the next younger cycle (MIS 25) as the Kaimatira Pumice Sand (Naish et al. 1998).

Typically, where reworking is not recognised as such for fossils, errors between one and many glacio-eustatic cycles in length will occur, say between 40 and 500 k.y. Ashes are less likely to survive multiple phases of reworking, and therefore do not commonly occur more than 1 cycle (40 k.y.) above their eruption position, except perhaps as isolated pumice pebbles.

Oceanographic or facies control errors

The error attached to the ranges of Pliocene-Pleistocene index fossils worldwide, and therefore their relative usefulness, is greatly influenced by the local tectonic and geographic situation. Over the last several million years, the New Zealand Plateau has been positioned in an exquisitely sensitive area for both tectonic and paleoceanographic change. First, NNE-trending displacements along both the Alpine Fault and the transcurrent and thrust faults in the North Island Hikurangi accretionary prism have caused the formation of a plethora of small, rapidly changing sedimentary basins (Vella & Briggs 1971; Carter & Carter 1982; Roberts & Wilson 1992) within which depths of sedimentary deposition, and hence facies, varied widely and rapidly. Accordingly, fossil groups may exhibit marked regional allopatric change (*Pelicaria*, rapidly changing species of which are often restricted to particular sedimentary basins; Neef 1970) and geographic partitioning (*Towaipecten ongleyi*, which is restricted to eastern North Island; Beu 1995). Both of these processes exercise a strong control on local age ranges on time-scales up to a million years or more. Second, during the late Cenozoic, important latitudinal frontal systems developed athwart the New Zealand Plateau (Vella 1973; Nelson & Cooke 2001; Carter et al. 2004). Today, the Subantarctic Front lies along the submerged southern and southeastern margin of the microcontinent (Campbell Plateau), and the Subtropical Front passes from the Tasman Sea to the Pacific Ocean by skirting South Island to the south and east, whence running eastward into the Pacific Ocean along the Chatham Rise. Many modern organisms have their geographic limits determined by these fronts or by current systems or oceanographic patterns (including temperature) related to them. Frontal development through the last several million years includes interaction between the fronts, a tectonically changing New Zealand archipelago, and a globally deteriorating and cyclic climate system. These interactions have had major effects on the distribution and age ranges of both benthic (often through larval distribution) and planktic organisms (Carter 2005).

For example, the single late Pliocene (Hautawan; c. 2.46 Ma) LO/HO appearance of *Zygochlamys delicatula* in Wanganui Basin (Fleming 1953) compared with its repetitive occurrence through the Hautawan (c. 2.25–1.97 Ma) of the Wairarapa Basin (Vella & Nicol 1970; Gammon 1997) must stem from a particular oceanographic linkage which caused north-travelling subantarctic waters to (unusually) disperse spat to the west (Fleming 1944), perhaps through the gap in the axial ranges at the Manawatu Strait (Grant-Taylor & Hornibrook 1964). Further, the HO of *Zygochlamys* in the Wairarapa stratigraphic record in the middle Nukumaruan reflects a rapid tectonic shoaling and eversion of the Mangaopari Basin at that time (e.g., Gammon 1997), and therefore probably does not mark the true moment of last occurrence of this taxon at this latitude. To take a second example, the spasmodic incidence through the Wanganui Pleistocene succession of warm-water guests such as *Pterotyphis zelandicus*, *Eunaticina*, *Zellipistes*, *Agnewia*, *Eunaticina*, *Bembicium melanostomum*, *Semicassis*, and *Pecten* (Finlay 1925; Fleming 1953; Beu 2004) similarly relates to the transmission there during particularly warm interglacials of pulses of subtropical water (the "Notonectian Current") derived from the East Australian Current system via either the West Coast or d'Urville Currents or, from the north, via the Tasman Front.

Given these and many other examples of tectonic or oceanographic control over New Zealand fossil ranges, it is not surprising that few of the favoured Pliocene-Pleistocene index fossils can be shown to have a countrywide synchrony when tested against independent time lines. For example, a survey of potential Pliocene-Pleistocene index fossils by Carter (2005, table 1) shows that, after more than 100 yr of intensive study, probably not one fossil LO or HO is yet demonstrated to be synchronous across all New Zealand's sedimentary basins. Clearly, we need to address the realities of New Zealand's recent geological and oceanographic history, and understand that it is unlikely that universally applicable biostratigraphic markers are going to emerge soon.

The bioevent error estimates summarised in Table 1 commonly attain 100 k.y or greater (i.e., they are much greater than the errors associated with astronomically tuned magnetic and cyclostratigraphy). Although biostratigraphy has played a vital historical role in building our understanding of New Zealand sedimentary basins, it has become apparent that fossil homotaxy is at best a blunt tool for countrywide correlation in the Pliocene-Pleistocene. The current use of interlocking networks of correlation criteria, linked to cyclostratigraphy, allows the determination of more accurate local fossil ranges without the prior assumption of their synchrony (e.g., Beu 2004). That by such a process we can now identify errors and simplifications in previous Pliocene-Pleistocene correlations is an indication of how far we have progressed. Future progress, however, depends upon biostratigraphic ranges in particular basins or regions being carefully related to the isochronous reference horizons—magnetic, isotopic, cyclostratigraphic, and tephrochronologic—which fortunately occur regularly throughout New Zealand successions.

THE PROPOSAL OF CARTER & NAISH (1998)

Influenced by the international developments in GSSP creation, and by the increasing numbers of tools available for correlation, New Zealand researchers started to move in the 1980s towards identifying more accurately, if not always defining, the base of each of the local Cenozoic stages (e.g., Beu et al. 1987; Morgans et al. 1999; Graham et al. 2000). These studies used both traditional biostratigraphic criteria and numeric techniques such as Sr-isotope dating. Because biostratigraphy alone was inadequate for correlating late Pliocene and Pleistocene strata, when they applied a similar methodology to the Wanganui stages, Carter & Naish (1998) took the further step of using tephrochronology and magnetostratigraphy to redefine stage bases (Fig. 1). In so doing, these authors were heeding the advice of Vella (1975, p. 91) who long ago understood that "the best hope for defining the true boundaries through all of the New Zealand Late Neogene is to use radiometric and paleomagnetic dates to calibrate sequences at appropriate places, and thus enable the use of endemic fossils as well as the few useful cosmopolitan ones"; they were also following established SSP precedents (e.g., Ogg 2003). At the same time, Carter and Naish took care to redefine the stage boundaries as close as possible to their traditional positions. Thus, they were primarily concerned with (1) improving the definition of the youngest parts of a de facto local time-scale; (2) thereby aiding all types of correlation; and (3) maintaining the stability of historical terminology, as indicated by Table 2.

It is apparent that the Carter & Naish (1998) boundary redesignations—with the single exception of the base-Marahauan, which it was seen as convenient to relocate at the Pliocene/Pleistocene boundary—all lie close to their traditional ages. The small shifts in stage boundaries recommended are at a level beyond discrimination by routine biostratigraphy (see previous discussion), and do not affect the stability of the historic stage system. In contrast, the radical and repeated changes in base-stage positions recommended for the Castlecliffian by Beu et al. (1987; base of Butlers Shell Conglomerate, 1.0 Ma), Beu (1995; base of Pahikura Pumice, 1.52 Ma; after Alloway et al. 1993), Beu et al. (cited in Beu 2001; top of Pukekiwi Shell Sand, 1.69 Ma) and Beu (2001; base of the Ototoka tephra, 1.62 Ma) are, cumulatively, causing nomenclatural mayhem. As Suggate (1989) wrote earlier in a discussion on New Zealand Quaternary nomenclature, it seems to be assumed that "an ability to subdivide suitably on the basis of evolutionary biostratigraphy is the sole criterion for producing subdivisions of the time scale", adding that the point is that a time-scale needs "to serve as many geologists as possible, rather than one particular group of them".

Despite the conservatism of Carter & Naish's (1998) redefinitions, Scott (2001) and Beu (2001) raised a number of objections to the proposals. These objections are discussed below, under subheadings appropriate to the points at issue.

Table 1 Estimated errors associated with various Pliocene-Pleistocene correlation techniques, listed in order of increasing error (bioevents marked by *).

	Technique	Typical error (k.y.)
	Magnetic reversal error	1–23 (nominal)
	Magnetic reversal error	20–100 (geological)
	Cyclostratigraphic error (cycle correct)	5–10
	Cyclostratigraphic error (cycle uncertain)	40–80
	Reworking (tephra)	5–80
*	Misjudgement/misidentification error	10–100
*	Microfossil sampling error	10–1000
	Numeric dating analytical error	30–150 (1% of age)
*	Reworking error (bioevent)	40–500
*	Dissolution error	40–500
*	Post-depositional error (bioevent)	120
	Post-depositional error (magnetic)	300
*	Homotaxial asynchrony	up to 1000
*	Facies/oceanographic error	up to 1000

Discussion

The distinction between definition and correlation

Many of the matters discussed in Scott (2001) and Beu (2001), and including most of the 12 "basic points" listed by Beu, deal with the recognition of particular events (usually biostratigraphic events) in many sections (i.e., with *correlation*). In contrast, Carter and Naish were proposing the objective *definition* of a set of local units which—irrespective of what views one may hold as to how they are or should be defined—are in daily use in New Zealand as a local *time-scale.* Whether or not there is a need for such a local time-scale can be debated, and is a matter to which I return below. But while a local time-scale exists, and is widely used, it needs to be properly defined. Confusion of the separate issues of definition and correlation has bedevilled stratigraphy for many decades. It is the great advantage of GSSPs that they, intentionally, lay such confusion to rest. I agree with Walsh (2005b) that it is redundant to define LSSPs after international GSSP-units have been created. In my view, the parallel definition of LSSPs can only be justified where there is an overriding need to provide unambiguous definition of a regional "time scale" that remains in active use.

Against this background, it is concerning to find confusion regarding New Zealand marine stages being perpetrated still in a recommended time-scale posted on the web by the Institute of Geological & Nuclear Sciences (GNS 2003; see Note Added in Proof, p. 624). As of mid-2003, for all but 4 of 24 local Cenozoic stages, GNS list the LO or HO of a benthic or planktic fossil taxon as the LSSP-defining event. Despite—or, in fact, because of—having separate columns in the table for "boundary defining event" and "boundary stratotype", the table fails to discriminate between stage definition and stage

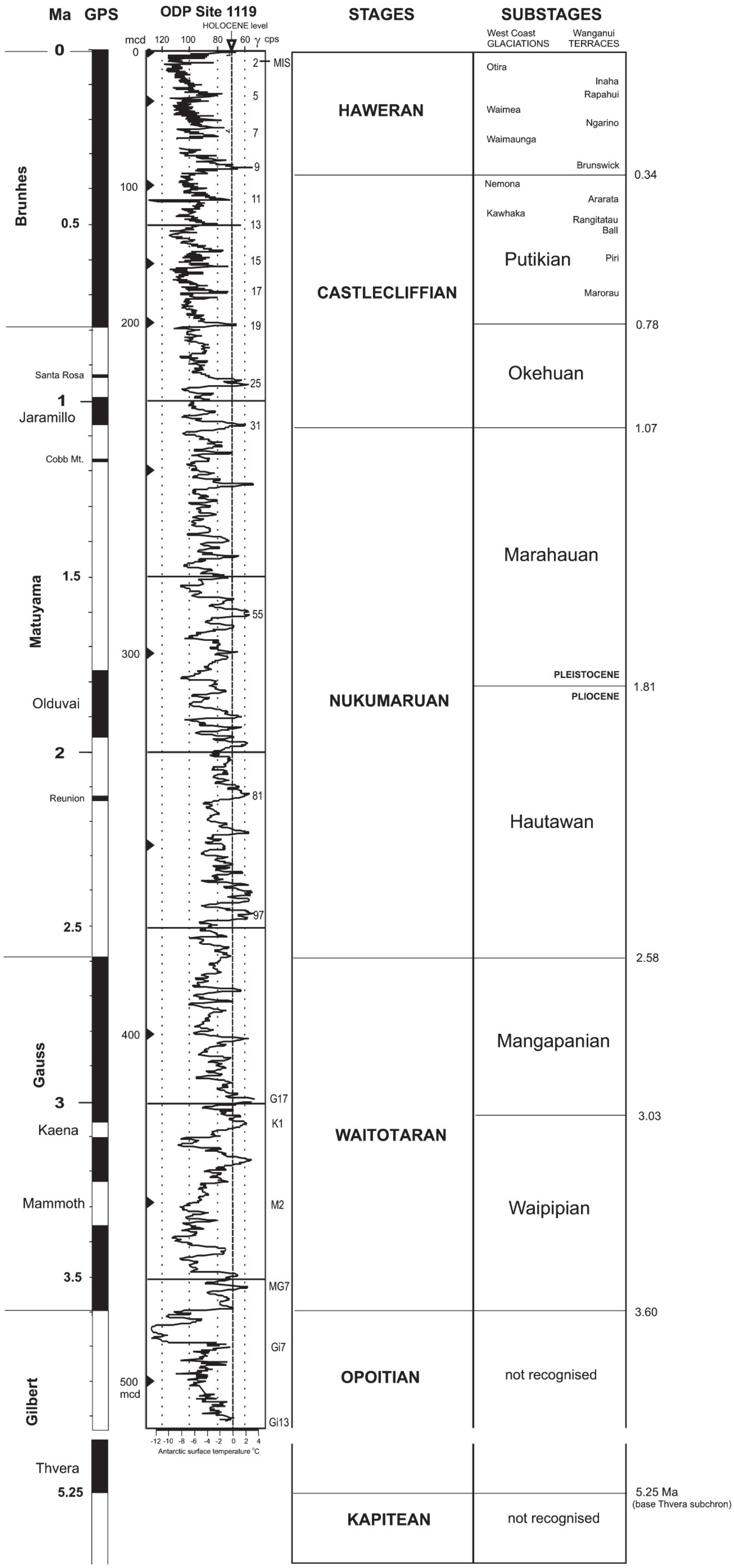

Fig. 1 Pliocene-Pleistocene stage classification for New Zealand after Carter & Naish (1998), set against the natural gamma ray climatic record of ODP Site 1119 (after Carter & Gammon 2004). Selected marine isotope stages are labelled after the numbering scheme of Lisiecki & Raymo (2005).

correlation. For example, under the column head "Lower boundary defining event (and currently used proxy)" the LO of *Phialopecten thomsoni* is listed as the LSSP for the Mangapanian (Sub)Stage. Even should there be agreement that *P. thomsoni* is the most useful taxon on which to base approximate correlation of the base-Mangapanian, which is unlikely, the prior suggested SSP definition (Beu et al. 1987) refers, properly, to the base of the shellbed in which the LO is located (i.e., the Mangapani Shellbed). The first occurrence of a fossil taxon (independently of a precise stratigraphic level in a nominated section) has not been acceptable for the definition of an SSP-marked age/stage boundary for more than 30 yr, and continuation of such practice, especially for Pliocene-Pleistocene strata, can only result in utter confusion.

In another departure from sound practice, GNS (2003) also list a new base-Castlecliffian marker at the base of the Ototoka Tephra, thus extending the length of the stage, truncating the subjacent Nukumaruan, and managing to ignore the principle of nomenclatural priority not once, but twice. First, because the historic definition of the base-Castlecliffian lies at the base of the Butlers Shell Conglomerate (Fleming 1953), c. 300 k.y. younger than the Ototoka Tephra, and second because an LSSP for the Castlecliffian has already been designated at the position of the base-Jaramillo Subchron, which approximates to the base of the Butlers Shell Conglomerate, by Carter & Naish (1998). As Aubry et al. (1999, p. 135) note with respect to analogous GSSP redefinitions of classic biostratigraphic stages, where "correlation precedes definition ... the result (is) that historical precedent is frequently sacrificed on the altar of attractive expediency". The loss of information, by rendering all earlier literature redundant, is a heavy price to pay.

Alternative means of defining the base of stages (SSP)

A second major problem with the approach recommended by Beu (2001) is its implied assertion that biostratigraphy should take precedence in the definition of time units *as of right*. For instance (Beu 2001, p. 117) writes that "The objective, scientific approach to chronostratigraphy is first to define the local biostratigraphic criteria and zonation to compile an objective time-scale...". This is a description of the confusing, historic European approach which SSP techniques were expressly designed to circumvent, and the "time-scales" which eventuate are far from objective. Thus, in recounting some of the many lengthy controversies which have accompanied interpretation of classic European sections, Aubry et al. (1999, p. 134) correctly warn us "that chronostratigraphy should never be contingent upon biostratigraphy".

In reality, biostratigraphy is only one of the numerous lines of evidence that need to be considered in choosing the location of a particular GSSP or LSSP (e.g., Remane et al. 1996); such choice is based properly on a knowledge of all available mechanisms of correlation. The paramountcy of biostratigraphy in matters of modern SSP definition, if any, relates only to the fact that fossils have played the central historical role in the recognition of most Phanerozoic stratigraphic divisions. Carter & Naish (1998) provided a thorough discussion of the advantages and disadvantages of using bioevents, paleomagnetic reversals, tephra, or isotope stages as LSSP markers in the New Zealand context. They concluded (p. 275) that "the best way of treating the traditional local stages is to use them for bundling a number of oxygen isotope stages in a way which respects traditional biostratigraphic distributions, but which is also based upon the more objective boundaries provided by either a magnetic reversal or by a widespread and distinctive volcanic ash". Based on this, these authors nominated a mix of tephrochronologic and magnetic criteria for fixing the LSSP for New Zealand Pliocene-Pleistocene stages. Over the last few years, precedents have been set for using magnetic reversals as criteria for the Paleogene/Neogene (Steininger et al. 1997), Miocene/Pliocene (Aubry et al. 1999), and middle/upper Pleistocene (Pillans 2003) boundaries. Magnetic chron designations are now routinely nominated as principal correlative events for all Cenozoic ages/stages (Ogg 2003; Gradstein et al. 2004)).

The need to use real physical markers, or their analogues, as SSP has now been understood for decades. A typical example of the problems associated with using biostratigraphic criteria instead is provided by the chaotic history of attempts to locate the Pliocene/Pleistocene boundary in its type area. There, traditional index fossils for the boundary have included *Arctica islandica*, *Hyalinea baltica*, and *Globorotalia truncatulinoides*. Selli (1967) and Bayliss (1969) showed that these species entered and re-entered at different stratigraphic levels in Calabrian sections, with Bayliss concluding "that the ranges of these species differ, even in sections which are comparatively close together and easily correlated on lithological characters". New Zealand Pliocene-Pleistocene index fossils are of course subject to similar facies and climatic controls as their Calabrian counterparts (e.g., Boreham 1963; Carter 2005), with a resulting biostratigraphic inconsistency that led Beu (1969) to even recommend dropping the Hautawan Substage on the grounds that it was faunally unrecognisable.

Table 2 Positions of the bases of Wanganui Series stages and substages, with age estimate for each, for comparison with the Wanganui LSSP recommended by Carter & Naish (1998).

	"Traditional" position	Estimated age of traditional position	LSSP as in Carter & Naish (1998)
Base Haweran	Top Putiki Shellbed	0.32	0.345
Base Putikian	L. Westmere Siltstone	0.77	0.78
Base Castlecliffian	Butlers Shell Conglomerate	1.07	1.07
Base Marahauan	Ohingaiti Sand	2.35	1.81
Base Nukumaruan	Hautawa Shellbed	2.46	2.58
Base Mangapanian	Mangapani Shell Conglomerate	3.04	3.03
Base Waitotaran	Pepper Shell Sand	c. 3.5	3.60
Base Opotian	Mapiri Group, Wairoa	c. 5.3	5.25

Yet, despite plentiful examples of its failure, as in Calabria, unrealistic biostratigraphic bias continues to pervade much New Zealand writing on stage definitions. For example, Morgans et al. (1996) list both the LO of *Zygochlamys delicatula* and *Globorotalia crassula* as index fossils for the base-Nukumaruan. The confusion as to which of these alternative taxa (not to mention in which section) is actually to be used in setting the LSSP results in an ambiguity of c. 300 k.y. In contrast, the uncertainty which results from Carter & Naish's (1998) designation of the base-Mangapanian located at the top of the Kaena Subchron is 8 k.y. (Lourens et al. 1996).

Finally, since Carter & Naish's (1998) discussion of these issues, an interesting complication has arisen regarding the establishment of the Oligocene/Miocene GSSP by Steininger et al. (1997) in the Lemme-Carrosio section in Italy, at an outcrop level which was intended to correspond to the C6Cn.2r/C6Cn.2n polarity boundary. As reported by Shackleton et al. (2000), later work suggests that the magnetic signature of the Lemme-Carrosio section does "not preserve a useful signal", making it unlikely that the GSSP—which was located by Steninger et al. at an apparent reversal at 31 m in the section, coinciding with the disappearance of the index nannofossil *Sphenolithus delphix*—corresponds precisely to the location of the polarity reversal (though Shackleton et al.'s analysis of DSDP Site 522 shows that these two events do indeed occur in close proximity to each other). In cases such as this, a decision is required as to whether to leave the GSSP in its initial ("incorrect") position, or to move it to correspond to the newly determined ("correct") position along with the reversal. Though relocation of a GSSP is allowed under agreed conditions, to take such an action casually of course defeats the whole point of the exercise. Even were it to be favoured, this option is not available for the Oligocene/Miocene boundary in its type locality because of the indeterminate nature of the paleomagnetic signature there. Problems such as these are therefore best addressed on a case-by-case basis. The New Zealand LSSP designations of Carter & Naish (1998) are based on analogue or surrogate markers (i.e., internationally established reversals or widely distributed ashes) rather than on physical markers in the outcrop of any single, specified section in which a nominated reversal or ash has been identified. They are "golden events" rather than "golden pegs", in the sense of Walsh et al. (2004). A benefit of this is that where a revision occurs in the local magnetostratigraphy, or in the interpretation of the ash, the position of the LSSP can simply be moved accordingly.

The primacy of biostratigraphy

One reason given by Beu (2001, p. 115) for the primacy of biostratigraphy is that it can provide estimates of the age of, and thereby serve to identify, particular state-changes within otherwise characterless binary signals such as a stratigraphic series of paleomagnetic reversals or numbered sedimentary cycles. However, Beu fails to consider, first, the often large absolute error associated with even those biostratigraphic age estimates which are adequate for such discrimination; and, second, the range of other techniques that can also be used for this purpose, which includes multiple types of numeric dating. Beu also fails to take account of two other standard working practices. The first, that once a particular binary event (e.g., the Gauss/Gilbert boundary) has been identified, perhaps using biostratigraphy as control, the 3.436 ± 0.013 Ma age of that horizon in the section is known with an accuracy which greatly exceeds that of working (homotaxial) biostratigraphy. The second, that the only biostratigraphic events that are known (as opposed to assumed) to be synchronous are those that have been tested against one of the numerically accurate binary or cyclic time series (e.g., Thierstein et al. 1977). Finally, the fact that biostratigraphy is often useful for the calibration of binary stratigraphic signals is in any case no argument for it to have primacy for the purposes of age/stage definition.

That bioevents are important tools for correlation is not in doubt. Their utility as a primary means for stage definition, on the presumption that their LO and HO in other sections will be the same as in the LSSP section—especially in the Pliocene-Pleistocene, where stratigraphic discrimination <10 k.y. has now become commonplace—is, however, much more open to question, for the following reasons:

- "as it has become possible to evaluate the continuity of the Cenozoic stratigraphic record, it has been shown that few sections yield LOs and HOs that accurately represent true first appearance datums (FADs) or last appearance datums (LADs) in the temporal sense" (Aubry et al. 1999, p. 134);
- "the great majority of bioevents have a local source (e.g., as in allopatric speciation) and thereafter disperse. Expectedly, most rates of dispersal are variable but are of significant duration" (Scott 2001, p. 601); Kucera & Kennett (2000) drew the obvious conclusion that every evolutionary event is diachronous, by definition;
- Miller (1990) has estimated c. 1 m.y. as the average error associated with Cenozoic foraminifer zonations; in a detailed quantitative examination of the dating potential of New Zealand Cenozoic microfossils, the modern basis for the stage classification, Cooper et al. (2001) showed that for 57 key bioevents that are used to estimate age, the minimum error is 1 m.y. and more typical errors are 2–4 m.y.;
- Cooper et al.'s study (2001, p. 1492) also showed that "several apparently reliable (bio)events appear in unexpected order in the composite and probable sequence. For example, the foraminifer *Globigerinoides trilobus* is ancestral to *G. bisphericus*, but the two last appearance events occur in the 'wrong' order".

Errors of such magnitude are simply no longer acceptable in Pliocene-Pleistocene studies, and most certainly not where criteria are being sought for stage definition.

Scott (2001) has also pointed out that bioevents in general are rather poorly suited to the definition of time-scales. Hence, his apparent preference—rather like Fleming (1953)—for viewing the New Zealand stages as biostratigraphic units with time-transgressive boundaries. Inconsistent with this, however, Scott also writes that "if the top of one unit defines the base of the succeeding unit, a classification of contiguous strata units is produced", as if this were a tenet of classic biostratigraphy and of traditional New Zealand stage usage. But it is not. Rather, the view is equivalent to the LSSP approach of Carter & Naish (1998), consistent with the GSSP approach of Remane et al. (1996) and with earlier roots in Campbell (1959) and George et al. (1969).

No matter how distinguished its history, or how much its component fossil groups may be loved, biostratigraphy occupies no special place within modern stratigraphy. The whole point of GSSP or LSSP definitions of time-scale units is to allow all criteria to be used equally for subsequent correlation purposes, irrespective of the specific reason (which might or might not be a bioevent in a particular section) for choice of the SSP.

Only events of evolutionary origin are unique

In a development on this theme, Scott comments that because New Zealand bioevents are unique events, occurring but once in the stratigraphic record, that "largely restricts the events to those of evolutionary origin".

This is simply not the case. Bioevents in particular successions can have a variety of causes. Some indeed are inferred to be evolutionary (e.g., *Orbulina* bioseries, Hornibrook in Wood 1969); others result from zoogeographic migration (e.g., *Jenkinsina samwelli*, Jenkins 1974; *Globorotalia crassiformis*, Scott et al. 1990), water mass change (*Catapsydrax dissimilis*, Vella 1973), climate change (*Globoquadrina dehiscens*, Scott 1992), or once-only facies change (*Ehrenbergina marwicki*, Morgans et al. 1999). It is, in fact, likely that most of the bioevents traditionally used to recognise the New Zealand stages (e.g., Thomson 1916; Finlay & Marwick 1940, 1947; Morgans et al. 1996) are not primarily of evolutionary origin but relate to one of the other possible causes for the appearance or disappearance of taxa.

Contrary to Scott's assertion, therefore, several different types of bioevent can carry the attributes of both uniqueness and homotaxy. But these characteristics make bioevents neither more nor less desirable as stratigraphic (SSP) marker points. Any candidate bioevent for an SSP has to be assessed on its merits against alternatives, which include other bioevents or altogether different types of evidence such as particular magnetic or isotopic changes.

If stage definitions are based on rigorous criteria, fossils may be used as an inaccurate proxy

Scott cautions against the use of magnetic boundaries for use as base-stage markers because, in the absence of magnetic evidence, fossils might be used as an inaccurate proxy. He cites as an example the case of the last occurrence of *Cibicides molestus*, which Hornibrook et al. (1989) believed was a "generally reliable event to mark the top of the Waipipian". In the absence of magnetic evidence, Scott asserts that this marker is not suitable for use as a proxy for the top of the Waipipian Substage (as currently positioned at the top-Kaena boundary, c. 3.091 Ma; Carter & Naish 1998), because it appears at c. 2.9 Ma in the Wanganui Basin (Naish et al. 1998) and at c. 2.3 Ma in the Wairarapa (Gammon 1997).

There are two aspects to this argument. The first is that accepting a top-Waipipian at 3.091 Ma means that one of the former biostratigraphic criteria for recognising that boundary is now significantly younger than the boundary. This objection is trivial, and will generally apply to all (except perhaps one) bioevents, or other correlation criteria, in relation to any agreed position for a stage-base. That a bioevent appears at a fixed time earlier or later than a particular boundary makes it no less useful as a correlation tool. Second is the more serious problem that *Cibicides molestus* seems to disappear from the record at different times in different sedimentary basins. Such is the real world. Which, ironically, has been revealed by testing the ranges of *Cibicides molestus* against the magnetic stratigraphy in each basin! In the absence of such tests, homotaxy only reigns, and we continue to make the blissful but wrong assumption that the disappearance of *Cibicides molestus* is everywhere synchronous.

All bioevents become more useful for correlation as they are able to be tested against independent age criteria in more and more locations. Thus tested, some bioevents prove to be excellent time proxies, and in fact as accurate as magnetic reversals or isotope events (e.g., Hays & Shackleton 1976; Thierstein et al. 1977). Others, even should they be immaculately homotaxial, provide crude age guidance only (e.g., Beu 1969; *Zygochlamys delicatula*). The key point is that the utility of bioevents for demarcating a stage boundary can only be assessed after the stage in question has had its base defined rigorously in a suitable section (by LSSP, or otherwise). The base may be defined to coincide with any one of a number of potential correlation criteria, including a magnetic boundary or a particular bioevent as known at the time. But after the LSSP is agreed, the criterion that was used to define the stage base at a particular level becomes just one, albeit an important one, of a number of criteria that are available for correlation. To argue otherwise is to argue for a return to the days when biostratigraphers assumed the right to move stage boundaries up or down depending upon the changing ranges of a key fossil or, worse, fossils.

Re-redefinition of Wanganui Stages in contravention of priority and sound stratigraphic practice

Beu (2001, pp. 120–123) discusses in detail the revision of the bases of most of the Wanganui stages and substages from the positions recommended by Carter & Naish (1998). Interestingly, he takes little issue with the principles of (1) redefining each historical stage "at a single point in a single section (standard section and point, SSP)" (p. 114), and (2) using physical criteria to establish such SSPs (two of his specific SSP recommendations being based on tephra). Rather, his primary concern is with the choice of the level at which each SSP should be situated. Carter & Naish's (1998) LSSP picks were, however, deliberately situated close to historical stage boundaries. Where Beu's recommendations depart widely from this, or where they ignore priority, they contravene sound stratigraphic practice and should be rejected, as discussed more fully in Appendix 1.

But do we need local stages anyway?

The discussion to this point has been based on the presumption that there is a need for a local New Zealand time-scale. The need is demonstrated not by logic, but rather by historical precedent plus widespread current use of the local stage system for all purposes to do with communicating the age of New Zealand's Cenozoic rocks. Starting with Carter (1974), and continuing up to Beu (2001) and Scott (2001), several researchers have questioned the need to use a set of local biostratigraphic zones as stage subdivisions on a time-scale, as follows:

(1) originally, New Zealand Cenozoic stages were set up as biostratigraphic zones, asserted later by Scott (1965) to be validated by their homotaxy and by Carter (1974) to correspond to oppelzones; Carter (1974) recommended, therefore, that use of the term stage should be discontinued, and zone substituted, so as to make the biostratigraphic nature of the "stages" clear;

(2) others preferred to continue with the stage terminology (e.g., Morgans et al. 1996; GNS 2003) and to locate stage-bases more accurately by identifying LSSP-equivalent

bioevents and estimating their numeric ages at stage type sections (e.g., Morgans et al. 1999; Graham et al. 2000); in deference to majority opinion, this approach was followed also by Carter & Naish (1998);

(3) Beu (2001, p. 117) remarks that "it is conceivable that international correlation eventually could reach a high enough level of precision that New Zealand stages could be abandoned in favour of the standard succession" and that during the Pliocene-Pleistocene "eventually, correlation could well be possible at the scale of individual oxygen istotope stages and this would provide the ideal subdivision of the local stages for particularly detailed geological purposes"; these comments accord with the course of action recommended by Carter (2005) and in this paper;

(4) Scott (2001) notes that the New Zealand stages—as homotaxial biostratigraphic units—may have boundaries that vary in age by up to hundreds of thousands of years from place to place. He then asks why one would want to bury more accurate stratigraphic signals (e.g., magnetic polarity change, or an isotope stage) "under the terminology of (such) a regional biostratigraphy?" Better by far to adopt the de facto international paleomagnetic/climatic cycle template for use in New Zealand and to use selected local bioevents, amongst other criteria, as "local chronostratigraphic proxies" (Scott 2001, p. 602). In essence, Scott challenges the need to redefine the bases of the New Zealand stages by any means, as opposed to continued testing of their validity as homotaxial oppelzones. It is hard to disagree with this logic, which is similar to that formerly expressed by Scott (1965) and Carter (1974), but the wider New Zealand stratigraphic community shows little sign of heeding such views and to date has strongly preferred use of the local stages as a time-scale;

(5) Walsh (1998, 2001) argues that once international GSSP-defined time-scale units are in place, the desirability of also creating regional LSSPs is far from obvious. For as Carter (1974, p. 198) commented, and still believes, once the Standard Stratigraphic Scale is adequately defined "there will be no need for formal local chronostratigraphies, though local biostratigraphic classifications will always be necessary due to the endemic nature of many faunas".

The LSSPs suggested by Carter & Naish (1998) were a purely pragmatic response to the strong desire of New Zealand stratigraphers to use an established biozonal system as the basis for a local time-scale (cf. Cooper 2004). The trenchant criticism of the proposals which was provided by Beu (2001) and Scott (2001) was therefore sweetly ironic, for Carter & Naish's main intention was to extend for a little longer the usefulness of the Pliocene-Pleistocene stage subdivisions in New Zealand. They answered the rhetorical title of their paper "Have local stages outlived their usefulness for the New Zealand Pliocene-Pleistocene?" with the comment: "Not quite yet ... but probably eventually". Given (1) the continuing advances in stratigraphic precision for dating young sediments in New Zealand, including some of the results of ODP Leg 181 drilling (e.g., Carter 2005; Naish et al. 2005); (2) the complex critiques by Beu (2001) and Scott (2001) of what were a small number of conservative changes to local stage definitions to make them more objective; and (3) the ambiguity introduced by the techniques of stage boundary definition adopted in Cooper (2004), it seems that "eventually" may have arrived.

CONCLUSIONS

Late Cenozoic events in New Zealand, both onland and at sea, are now best referred to within the chronologic framework of the international time-scale, as currently fashioned from paleomagnetic reversal history and astonomical tuning of the oxygen isotope and other cyclic climatic time series. This chronology is already in use for offshore marine data by Nelson et al. (1993) and Hall et al. (2001), onland Quaternary strata by the national geological mapping agency (e.g., Turnbull 2000), onland marine strata by Saul et al. (1999), and onland glacial deposits by Suggate & Waight (1999). To aid in this task, the ODP Site 1119 record presents itself as a high quality and essentially uninterrupted local climate record back to at least 2.5 Ma, and probably to 3.91 Ma (Carter & Gammon 2004; Carter 2005). The 1–2 k.y.-resolution natural gamma record from the site reflects well the MIS climate cycles of the oceanic isotope record, and can thereby be correlated with other extended climatic time series such as those from the polar ice caps (Petit et al. 1999), lakes (Hooghiemstra 1989), and marine sediments (Lourens et al. 1996).

Following QMAP practice, therefore, it is recommended that international magnetic chron and oxygen isotope divisions be used for referring to the age of New Zealand Pliocene-Pleistocene rocks back to 4 Ma, and perhaps beyond to the base of the Pliocene (c. 5.2 Ma) (Fig. 1).

Zalasiewicz et al. (2004) have recently resurrected the debate about the need for both chronostratigraphic (stage) and chronologic (age) units. These authors recommend that chronostratigraphic units be discontinued, and that the standard stratigraphic time scale in future be couched in terms of chronologic ages. If this long-overdue rationalisation comes to fruition, two options will exist for the continuation of the local New Zealand biostratigraphic scheme. A first option is that the local stages that currently lack rigorously specified LSSPs at their base could be provided with them, and the stages could then assume their correct (for a time-scale) age label. Alternatively—and consistent with the recommendations and discussion of Fleming (1953), Scott (1965, 2001), Carter (1974), and parts of Walsh (1998, 2001, 2004)—the stages might be rebadged as homotaxial oppelzones for use in biostratigraphic correlation. In such a scheme "the fixing of a type formation for a stage does not fix the limits of the stage any more than selection of a type specimen (in zoology) fixes the limits of a species. The boundaries of stages and substages are determined by study of faunal changes in the whole standard section and in supplementary sections" (Fleming 1953, p. 102). The history of New Zealand stratigraphic classification suggests that, cogent arguments against it notwithstanding (e.g., Walsh 2005b), the first of these options is the more likely to eventuate.

The task ahead of us is to use all available techniques so that our studies of the New Zealand Pliocene-Pleistocene make a maximum contribution to the understanding of global environmental and climatic history. Towards that end, stability of nomenclature is paramount. At the moment, international subdivisions of the Pliocene-Pleistocene are stable and readily applied, whereas New Zealand subdivisions are far from agreed and, when biostratigraphic, generally basin-restricted in their application.

ACKNOWLEDGMENTS

Stratigraphy is best rooted in fieldwork. I therefore acknowledge with appreciation many spirited discussions with colleagues during field studies of New Zealand successions, foremost amongst them Doug Campbell, Hamish Campbell, John Beggs, Graham Bishop, Chuck Landis, Ian Turnbull, Alan Beu, Doug Haywick, Tim Naish, Steve Abbott, Mike Isaacs, Brent Alloway, and Brad Pillans. Whilst absolving these persons from complicity in the views expressed in this paper, which are mine alone, their friendly critical attention has certainly served to hone the logic. I also appreciate the constructive efforts made by referees Brad Pillans and Steve Walsh to improve both the logic and style of the manuscript, and thank George Scott and Bruce Hayward for sharing with me many unpublished data regarding the ranges of Pliocene-Pleistocene planktonic foraminifera. Financial support for this research was provided by the Australian Research Council, grants A-39805139 and DP 0344080.

REFERENCES

Abbott ST, Carter RM 1994. The sequence architecture of mid-Pleistocene (0.35–0.95 Ma) cyclothems from New Zealand: facies development during a period of known orbital control on sea-level cyclicity. In: de Boer PL, Smith DG ed. Orbital forcing and cyclic sequences. International Association of Sedimentologists Special Publication 19: 367–394.

Abbott ST, Carter RM 1999. Stratigraphy of the Castlecliffian type section: ten mid-Pleistocene sequences from the Wanganui coast, New Zealand. New Zealand Journal of Geology and Geophysics 42: 91–111.

Ager DV 1973. The nature of the stratigraphical record. London, J. Wiley & Sons.

Allan RS 1933. On the System and Stage names applied to subdivisions of the Tertiary strata in New Zealand. Transactions of the New Zealand Institute 63: 81–108.

Alloway BW, Pillans BJ, Sandhu AS, Westgate JS 1993. Revision of the marine chronology in the Wanganui Basin, New Zealand, based on the isothermal plateau fission-track dating of tephra horizons. Sedimentary Geology 82: 299–310.

Aubry M-P, Berggren WA, Van Couvering JA, Steininger F 1999. Problems in chronostratigraphy: stages, series, unit and boundary stratotypes, global stratotype section and point and tarnished golden spikes. Earth-Science Reviews 46: 99–148.

Bayliss DD 1969. The distribution of *Hyalinea balthica* and *Globorotalia truncatulinoides* in the type Calabrian. Lethaia 2: 133–143.

Berger A, Loutre MF 1991. Insolation values for the climate of the last 10 m.y. Quaternary Science Reviews 10: 297–317.

Beu AG 1969. Index macrofossils and New Zealand Pliocene and lower Pleistocene time-stratigraphy. New Zealand Journal of Geology and Geophysics 12: 643–658.

Beu AG 1978. Taxonomy and biostratigraphy of large New Zealand Pliocene Pectinidae (*Phialopecten* and *Mesopeplum*). New Zealand Journal of Geology and Geophysics 21: 243–269.

Beu AG 1995. Pliocene limestones and their scallops. Lithostratigraphy, pectinid biostratigraphy and paleogeography of eastern North Island late Neogene limestone. New Zealand Institute of Geological & Nuclear Sciences Monograph 10. 243 p.

Beu AG 2001. Local stages to be used for the Wanganui Series (Pliocene-Pleistocene) and their means of definition. New Zealand Journal of Geology and Geophysics 44: 113–125.

Beu AG 2004. Marine Mollusca of oxygen isotope stages of the last 2 million years in New Zealand. Part 1: Revised generic positions and recognition of warm-water and cool-water migrants. Journal of the Royal Society of New Zealand 34: 111–265.

Beu AG, Edwards AR 1984. New Zealand Pleistocene and Late Pliocene glacio-eustatic cycles. Palaeogeography, Palaeoclimatology, Palaeoecology 46: 119–142.

Beu AG, Maxwell PA 1990. Cenozoic Mollusca of New Zealand. New Zealand Geological Survey Paleontological Bulletin 58. 518 p.

Beu AG, Edwards AR, Pillans BJ 1987. A review of New Zealand Pleistocene stratigraphy, with emphasis on the marine rocks. In: Itihara M, Kamei T ed. Proceedings of the 1st International Colloquium on Quaternary Stratigraphy of Asia and Pacific Area, Osaka. Pp. 250–269.

Boreham AUE 1963. Some problems concerning the application of the Lower Nukumaruan (Hautawan) Substage (lower Pleistocene, New Zealand). New Zealand Journal of Geology and Geophysics 6: 3–27.

Campbell JD 1959. The Warepan Stage (Triassic); definition and correlation. New Zealand Journal of Geology and Geophysics 2: 198–207.

Carter RM 1970. A proposal for the subdivision of Tertiary time in New Zealand. New Zealand Journal of Geology and Geophysics 13: 350–363.

Carter RM 1972. Wanganui strata of Komako District, Pohangina Valley, Ruahine Range, Manawatu. Journal of the Royal Society of New Zealand 2: 293–324.

Carter RM 1974. A New Zealand case-study of the need for local time-scales. Lethaia 7: 181–202.

Carter RM 2005. A New Zealand climatic template back to c. 3.9 Ma: ODP Site 1119, Canterbury Bight, south-west Pacific Ocean, and its relationship to onland successions. Journal of the Royal Society of New Zealand 35: 9–42.

Carter RM, Carter L 1982. The Motunau Fault and other structures at the southern edge of the Australian-Pacific plate boundary, offshore Marlborough, New Zealand. Tectonophysics 88: 133–159.

Carter RM, Gammon P 2004. New Zealand maritime glaciation: millennial-scale southern climate change since 3.9 Ma. Science 304: 1659–1662.

Carter RM, Naish TR 1998. Have local stages outlived their usefulness for the New Zealand Pliocene-Pleistocene? New Zealand Journal of Geology and Geophysics 41: 271–279.

Carter RM, McCave IN, Richter C, Carter L and others 1999. Southwest Pacific gateways, Sites 1119–1125. Proceedings of Ocean Drilling Program Initial Reports 181: 1–112 + CD-ROM.

Carter RM, McCave IN, Carter L 2004. Fronts, flows, drifts, volcanoes, and the evolution of the southwestern gateway to the Pacific Ocean. In: Proceedings of Ocean Drilling Program, Scientific Reports 181: 1–111.

Cooper RA ed. 2004. The New Zealand geological timescale. Institute of Geological & Nuclear Sciences Monograph 22. 284 p.

Cooper RA, Crampton JS, Raine JI, Gradstein FM, Morgans HEG, Sadler PM, Strong CP, Waghorn D, Wilson GJ 2001. Quantitative biostratigraphy of the Taranaki Basin, New Zealand: a deterministic and probabilistic approach. American Association of Petroleum Geologists Bulletin 85: 1469–1498.

Emiliani C 1966. Paleotemperature analysis of Caribbean cores P6403-8 and P6304-9 and a generalized temperature curve for the past 425,000 years. Journal of Geology 74: 109–124.

Finlay HJ 1925. Some modern conceptions applied to the study of the Cainozoic Mollusca of New Zealand. Verhandelingen Geologisch-Mijnbouwkundig Genootschap Nederland Geologische Serie VIII: 161–172.

Finlay HJ, Marwick J 1940. The divisions of the Upper Cretaceous and Tertiary of New Zealand. Transactions of the Royal Society of New Zealand 70: 77–135.

Finlay HJ, Marwick J 1947. New divisions of the Upper Cretaceous and Tertiary in New Zealand. New Zealand Journal of Science and Technology B28: 228–236.

Fleming CA 1944. Molluscan evidence of Pliocene climatic change in New Zealand. Royal Society of New Zealand Transactions 74: 207–220.

Fleming CA 1947. Standard sections and subdivisions of the Castlecliffian and Nukumaruan Stages in the New Zealand Pliocene. Royal Society of New Zealand Transactions 76: 300–326.

Fleming CA 1953. The geology of the Wanganui Subdivision, Waverley and Wanganui sheet districts (N137 and N138). New Zealand Geological Survey Bulletin 52: 1–362.

Gammon PR 1997. Sequence stratigraphy of Mangaopari Basin, southeastern North Island, New Zealand. Unpublished PhD dissertation, James Cook University, Townsville, Australia.

George TN, Harland WB, Ager DV, and others 1969. Recommendations on stratigraphical usage. Geological Society of London Proceedings 1656: 139–166.

Geyh MA, Schleicher H 1990. Absolute age determination. Springer-Verlag. 503 p.

GNS 2003. Interim New Zealand geological timescale. http://gns.cri.nz/what/earthhist/dating/nzgt0603.xls [June 2003]

Gradstein F, Ogg J, Smith A 2004. A geologic time scale 2004. 3rd ed. Cambridge University Press. 589 p.

Graham IJ, Morgans HE, Waghorn DB, Trotter JA, Whitford DA 2000. Strontium isotope stratigraphy of the Oligocene-Miocene Otekaike Limestone (Trig Z section) in southern New Zealand: age of the Duntroonian/Waitakian boundary. New Zealand Journal of Geology and Geophysics 43: 335–347.

Grant-Taylor TL, Hornibrook N de B 1964. The Makara faulted outlier and the age of Cook Strait. New Zealand Journal of Geology and Geophysics 7: 299–313.

Hall IR, McCave IN, Shackleton NJ, Weedon GP, Harris SE 2001. Glacial intensification of deep Pacific inflow and ventilation. Nature 412: 809–811.

Hays JD, Shackleton NJ 1976. Globally synchronous extinction of the radiolarian *Stylatractus universus*. Geology 4: 649–652.

Haywick DW 1990. Stratigraphy, sedimentology, palaeoecology and diagenesis of the Petane Group (Plio-Pleistocene) in the Tangoio Block, central Hawke's Bay, New Zealand. Unpublished PhD dissertation, James Cook University, Townsville, Australia.

Hedberg HD ed. 1976. International stratigraphic guide. New York, J.Wiley & Sons. 200 p.

Hilgen FJ 1987. Sedimentary rhythms and high-resolution chronostratigraphic correlations in the Mediterranean Pliocene. Newsletters in Stratigraphy 17: 109–127.

Hilgen FJ 1991. Astronomical calibration of Gauss to Matuyama sapropels in the Mediterranean and implication for the Geomagnetic Polarity Time Scale. Earth and Planetary Science Letters 104: 226–244.

Hooghiemstra H 1989. Quaternary and Upper Pliocene glaciations and forest development in the tropical Andes: evidence from a long high-resolution pollen record from the sedimentary basin of Bogota, Columbia. Palaeogeography, Palaeoclimatology, Palaeoecology 72: 11–26.

Hornibrook N de B 1976. *Globorotalia truncatulinoides* and the Pliocene-Pleistocene boundary in northern Hawkes Bay, New Zealand. In: Takayanagi Y, Saito T ed. Progress in micropaleontology. New York, Micropaleontology Press. Pp. 83–102.

Hornibrook N de B 1980. Correlation of Pliocene biostratigraphy, magnetostratigraphy and O^{18} fluctuations in New Zealand and DSDP Site 284. Newsletters in Stratigraphy 9: 114–120.

Hornibrook N de B, Brazier RC, Strong CP 1989. Manual of New Zealand Permian to Pleistocene foraminiferal biostratigraphy. New Zealand Geological Survey Paleontological Bulletin 56.

Jenkins DG 1974. Initiation of the proto Circum-Antarctic Current. Nature 252: 371–373.

Journeaux TD, Kamp PJJ, Naish T 1996. Middle Pliocene cyclothems, Mangaweka region, Wanganui Basin, New Zealand: a lithostratigraphic framework. New Zealand Journal of Geology and Geophysics 39: 135–149.

Kucera M, Kennett JP 2000. Biochronology and evolutionary implications of late Neogene California margin planktonic foraminiferal events. Marine Micropaleontology 40: 67–81.

Lisiecki LE, Raymo ME 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records. Paleoceanography 20: PA 1003, doi:10.1029/2004PA001071.

Lourens LJ, Antonarakou A, Hilgen FJ, Van Hoof AAM, Vergnaud-Grazzini C, Zachariasse WJ 1996. Evaluation of the Plio-Pleistocene astronomical timescale. Paleoceanography 11: 391–413.

McIntyre AP, Kamp PJJ 1998. Late Pliocene (2.8–2.4 Ma) cyclothemic shelf deposits, Parikino, Wanganui Basin, New Zealand: lithostratigraphy and correlation of cycles. New Zealand Journal of Geology and Geophysics 41: 69–84.

McLaren DJ 1977. The Silurian-Devonian Boundary Committee: a final report. In: Martinson A. ed. The Silurian-Devonian boundary. IUGS Series A5. E. Schweizerbart'sche Velagsbuchhandlung. 34 p.

Miller KG 1990. Recent advances in Cenozoic marine stratigraphic resolution. Palaios 5: 301–302.

Morgans HEG, Scott GH, Beu AG, Graham IJ, Mumme TC, St George W, Strong CP 1996. New Zealand Cenozoic time scale. New Zealand Institute of Geological & Nuclear Sciences Science Report 96/38.

Morgans HEG, Edwards AR, Scott GH, Graham IJ, Kamp PJJ, Mumme TC, Wilson GJ, Wilson GS 1999. Integrated biostratigraphy of the Waitakian-Otaian boundary stratotype, early Miocene, New Zealand. New Zealand Journal of Geology and Geophysics 42: 581–614.

Naish TR, Kamp PJJ 1997. Sequence stratigraphy of sixth-order (41 k.y.) Pliocene-Pleistocene cyclothems, Wanganui Basin, New Zealand: a case for the regressive systems tract. Geological Society of America Bulletin 109: 978–999.

Naish TR, Kamp PJJ, Alloway BV, Pillans BJ, Wilson GS, Westgate JA 1996. Integrated tephrochronology and magnetostratigraphy for cyclothemic marine strata Wanganui Basin: implications for the Pliocene-Pleistocene boundary in New Zealand. Quaternary International 34–36: 29–48.

Naish T, Abbott ST, Alloway BV, Beu AG, Carter RM, Edwards AR, Journeaux TJ, Kamp PJJ, Pillans BJ, Saul GS, Woolfe KJ 1998. Astronomical calibration of a southern hemisphere Plio-Pleistocene reference section, Wanganui Basin, New Zealand. Quaternary Science Reviews 17: 695–710.

Naish TR, Field BD, Zhu H, Melhuish A, Carter RM, Abbott ST, Edwards S, Alloway BV, Wilson GS, Niessen F, Barker A, Browne GH, Maslen G 2005. Integrated outcrop, drill core, borehole and seismic stratigraphic architecture of a cyclothemic, shallow-marine depositional system, Wanganui Basin, New Zealand. Journal of the Royal Society of New Zealand 35: 91–122.

Neef G 1970. Notes on the subgenus *Pelicaria*. New Zealand Journal of Geology and Geophysics 13: 436–476.

Nelson CS, Cooke PJ 2001. History of oceanic front development in the New Zealand sector of the Southern Ocean during the Cenozoic—a synthesis. New Zealand Journal of Geology and Geophysics 44: 535–553.

Nelson CS, Cooke PJ, Hendy CH, Cuthbertson AM 1993. Oceanographic and climate changes over the past 150,000 years at Deep Sea Drilling Project Site 594 off southeastern New Zealand, southwest Pacific Ocean. Paleoceanography 8: 435–458.

Ogg J 2003. Overview of Global Boundary Stratotype Sections and Points (GSSP's). http://www.stratigraphy.org/gssp.htm.

Penck A, Bruckner E 1909. Die Alpen im Eiszeitalter. Leipzig, Tachnitz.

Petit JR, Jouzel J, Raynaud D and others 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. Nature 399: 429–436.

Pillans B 2003. Subdividing the Pleistocene using the Matuyama Brunhes boundary (MBB): an Australasian perspective. Quaternary Science Reviews 22: 1569–1577.

Pillans BJ, Roberts AP, Wilson GS, Abbott ST, Alloway BV 1994. Magnetostratigraphic, lithostratigraphic and tephrostratigraphic constraints on Lower and Middle Pleistocene sea-level changes. Earth and Planetary Science Letters 121: 81–98.

Pillans B, Kohn BP, Berger G, Froggatt P, Duller G, Alloway B, Hesse P 1996. Multi-dating comparison for mid-Pleistocene Rangitawa Tephra, New Zealand. Quaternary Science Reviews 15: 641–653.

Prevot M, Mankinen EA, Gromme CS, Coe RS 1985. How the geomagnetic field vector reverses polarity. Nature 316: 230–234.

Raffi I, Backman J, Rio D, Shackleton NJ 1993. Plio-Pleistocene nannofossil biostratigraphy and calibration to oxygen isotope stratigraphies from Deep Sea Drilling Project 607 and Ocean Drilling Program Site 677. Paleoceanography 8: 387–408.

Raymo ME, Ruddiman WF, Backman J, Clement BM, Martinson DG 1989. Late Pliocene variation in Northern Hemisphere ice sheets and North Atlantic deep water circulation. Paleoceanography 4: 413–446.

Remane J, Bassett MG, Cowie JW, Gohrbandt KH, Lane HR, Michelsen O, Naiwen W 1996. Revised guidelines for the establishment of global chronostratigraphic standards by the International Commission on Stratigraphy (ICS). Episodes 19: 77–81.

Rio D 1982. The fossil distribution of coccolithophore genus *Gephyrocapsa* Kamptner and related Plio-Pleistocene chronostratigraphic problems. In: Prell WL et al. Deep Sea Drilling Project Initial Reports 68: 325–343. Washington, United States Government Printing Office.

Roberts AP, Turner GM 1993. Diagenetic formation of ferrimagnetic iron sulphide minerals in rapidly deposited marine sediments, South Island, New Zealand. Earth and Planetary Science Letters 115: 257–273.

Roberts AP, Wilson GS 1992. Stratigraphy of the Awatere Group, Marlborough, New Zealand. Journal of the Royal Society of New Zealand 22: 187–204.

Ruddiman WE, Raymo ME, Martinson DG, Clement BM, Backman J 1989. Pleistocene evolution: Northern Hemisphere ice sheets and North Atlantic Ocean. Paleoceanography 4: 353–412.

Salvador A ed. 1994. International stratigraphic guide. 2nd ed. International Subcommission on Stratigraphic Classification of IUGS International Commission on Stratigraphy.

Saul G, Naish TR, Abbott ST, Carter RM 1999. Sedimentary cyclicity in the marine Plio-Pleistocene of Wanganui Basin (N.Z.): sequence stratigraphic motifs characteristic of the last 2.5 Ma. Geological Society of America Bulletin 111: 524–537.

Schenck HG, Muller SW 1941. Stratigraphic terminology. Geological Society of America Bulletin 51: 1397–1412.

Scott GH 1965. Homotaxial stratigraphy. New Zealand Journal of Geology and Geophysics 8: 859–862.

Scott GH 1972. Revision of Hutchinsonian, Awamoan and Altonian Stages (Lower Miocene, New Zealand)—2. New Zealand Journal of Geology and Geophysics 15: 49–70.

Scott GH 1992. Planktonic foraminiferal biostratigraphy (Altonian-Tongaporutuan Stages, Miocene) at DSDP Site 593, Challenger Plateau, Tasman Sea. New Zealand Journal of Geology and Geophysics 35: 501–513.

Scott GH 2001. Have local stages outlived their usefulness for the New Zealand Pliocene-Pleistocene? Letter to the Editor. New Zealand Journal of Geology and Geophysics 44: 601–602.

Scott GH, Bishop S, Burt BJ 1990. Guide to some Neogene globorotalids (Foraminiferida) from New Zealand. New Zealand Geological Survey, Paleontological Bulletin 61. 135 p.

Selli R 1967. The Pliocene-Pleistocene boundary in Italian marine sections and its relationship to continental stratigraphies. Progress in Oceanography 4: 67–86.

Seward D 1974. Age of New Zealand Pleistocene substages by fission-track dating of glass shards from tephra horizons. Earth and Planetary Science Letters 24: 242–248.

Seward D 1976. Tephrostratigraphy of the marine sediments in the Wanganui Basin, New Zealand. New Zealand Journal of Geology and Geophysics 19: 9–20.

Shackleton NJ, Opdyke ND 1973. Oxygen isotope and palaeomagnetic stratigraphy of equatorial Pacific core V28-238: oxygen isotope temperatures and ice volumes on a 10^5 and 10^6 year scale. Quaternary Research 3: 39–55.

Shackleton NJ, Opdyke ND 1976. Oxygen isotope and paleomagnetic stratigraphy of Pacific core V28-239 late Pliocene to latest Pleistocene. Geological Society of America Memoir 145: 449–464.

Shackleton NJ, Berger A, Peltier WR 1990. An alternative astronomical calibration of the lower Pleistocene timescale based on ODP Site 677. Transactions of the Royal Society of Edinburgh 81: 251–261.

Shackleton NJ, Hall MA, Raffi I, Tauxe L, Zachos J 2000. Astronomical calibration age for the Oligocene-Miocene boundary. Geology 28: 447–450.

Shane P, Froggatt P, Black T, Westgate J 1995. Chronology of Pliocene and Quaternary bioevents and climatic events from fission-track ages on tephra beds, Wairarapa, New Zealand. Earth and Planetary Science Letters 130: 141–154.

Steininger FF, Aubry MP, Berggren WA, Biolzi M, Borsetti AM, Cartlidge JE, Cati F, Corfield R, Gelati R, Iaccarino S, Napoleone C, Ottner F, Rogl F, Roetzel R, Spezzaferri S, Tateo F, Villa G, Zevenboom D 1997. The global stratotype and point (GSSP) for the base of the Neogene. Episodes 20: 23–28.

Suggate RP 1989/90. What happened to the Quaternary? Geological Society of New Zealand Newsletter: 85–86.

Suggate RP, Waight TE 1999. Geology of the Kumara-Moana area. Sheets J32 and part K32, 1:50 000. Institute of Geological & Nuclear Sciences Geological Map 23. 124 p.

Te Punga MT 1952. The geology of Rangitikei Valley. New Zealand Geological Survey Memoir 8.

Thierstein HR, Geitzenauer KR, Molfino B, Shackleton NJ 1977. Global synchroneity of late Quaternary coccolith datum levels: validation by oxygen isotopes. Geology 5: 400–404.

Thomson JA 1916. On the stage names applicable to the divisions of the Tertiary in New Zealand. Transactions of the New Zealand Institute 48: 28–40.

Tiedemann R, Sarnthein M, Shackleton NJ 1994. Astronomic timescale for the Pliocene Atlantic $\delta^{18}O$ and dust flux records of Ocean Drilling Program site 659. Paleoceanography 9: 619–638.

Turnbull IM 2000. Geology of the Wakatipu area. Institute of Geological & Nuclear Sciences 1:250 000 Geological Map 18. 1 sheet + 72 p.

Turner GM, Kamp PJJ 1990. Palaeomagnetic location of the Jaramillo Subchron and the Matuyama-Brunhes transition in the Castlecliffian stratotype section, Wanganui Basin, New Zealand. Earth and Planetary Science Letters 100: 42–50.

Vella P 1973. Ocean paleotemperatures and oscillations of the Subtropical Convergence Zone on the eastern side of New Zealand. In: Fraser R ed. Oceanography of the South Pacific. Pp. 315–318.

Vella P 1975. The boundaries of the Pliocene in New Zealand. In: Saito T, Burkle LH ed. Late Neogene epoch boundaries. Special Publication 1. New York, Micropalaeontology Press. Pp. 85–93.

Vella P, Briggs WM 1971. Lithostratigraphic names, upper Miocene to lower Pleistocene, northern Aorangi Range, Wairarapa. New Zealand Journal of Geology and Geophysics 14: 253–274.

Vella P, Nicol ER 1970. *Chlamys delicatula* and the Hautawan Stage. New Zealand Journal of Geology and Geophysics 13: 873–876.

Walsh SL 1998. Fossil datum terms, paleobiological event terms, paleontostratigraphy, chronostratigraphy, and the definition of land mammal "age" boundaries. Journal of Vertebrate Paleontology 18: 150–179.

Walsh SL 2000. Eubiostratigraphic units, quasibiostratigraphic units, and "assemblage zones". Journal of Vertebrate Paleontology 20: 761–775.

Walsh SL 2001. Notes on geochronologic and chronostratigraphic units. Geological Society of America Bulletin 113: 704–713.

Walsh SL 2003. Notes on geochronologic and chronostratigraphic units—Reply. Geological Society of America Bulletin 115: 1017–1019.

Walsh SL 2004. Solutions in chronostratigraphy: the Paleocene/Eocene boundary debate, and Aubry vs. Hedberg on chronostratigraphic principles. Earth-Science Reviews 64: 119–155.

Walsh SL 2005a. The role of stratotypes in stratigraphy Part 2. The debate between Kleinpell and Hedberg, and a proposal for the codification of biochronologic units. Earth-Science Reviews 70: 47–73.

Walsh SL 2005b. The role of stratotypes in stratigraphy Part 3. The Wood Committee, the Berkeley school of North American mammalian stratigraphic paleontology, and the status of provincial golden spikes. Earth-Science Reviews 70: 75–101.

Walsh SL, Gradstein FM, Ogg JG 2004. History, philosophy, and application of the Global Stratotype Section and Point (GSSP). Lethaia 37: 201–218.

Weaver PPE, Carter L, Neil H 1998. Response of surface watermasses and circulation to late Quaternary climate change, east of New Zealand. Paleoceanography 13: 70–83.

Wood BL 1969. Geology of Tuatapere Subdivision, Western Southland. New Zealand Geological Survey Bulletin 79. 162 p.

Zalasiewicz J, Smith A, Brenchley P, Evans J, Knox R, Riley N, Gale A, Gregory FJ, Rushton A, Gibbard P, Hesselbo S, Marshall J, Oates M, Rawson P, Trewin N 2004. Simplifying the stratigraphy of time. Geology 32: 1–4.

Appendix 1 over page

APPENDIX 1 Criteria for LSSP designation for New Zealand Pliocene-Pleistocene Stages.

Beu (2001, pp. 119–123) provides an extended commentary on the biostratigraphy of the stages and substages of the Wanganui Series. Though he generally supports the concept of defining the stages by LSSP at their bases, at the same time he recommends (1) discarding the substages of the Castlecliffian and Nukumaruan, (2) continuing the use of the substages of the Waitotaran (the Waipipian and Mangapanian) as full stages, (3) changes to both long recognised and recently designated stage-bases, and (4) leaving some LSSP (Waitotaran and Opoitian) undesignated until further studies are completed. Many of these recommendations contravene sound stratigraphic practice, as discussed further below.

Stages

Haweran: Carter & Naish (1998) and Beu (2001) are in agreement that the base of the Haweran should be taken at the base of the Rangitawa Tephra, currently estimated at 0.345 Ma (Pillans et al. 1996).

Castlecliffian: Though the stage was introduced by Thomson (1916), the base of the Castlecliffian was first systematised at the base of the Butlers Shell Conglomerate (= base of unit CL1, Ototoka shell conglomerate) by Fleming (1947). This designation was confirmed by Fleming (1953), notwithstanding Te Punga's (1952) correlation of base-Castlecliffian to the stratigraphically higher Pakihikura Pumice in the nearby Rangitikei section. The base-Butlers horizon has a currently estimated age of 1.07 Ma (Abbott & Carter 1999), and was accepted by all subsequent writers up until Beu (1995). Following earlier suggestions by Alloway et al. (1993) and Beu (1995, p. 8) to move the base-Castlecliffian boundary down to the top of the Pukekiwi Shell Sand in the Wanganui coast section (basin cycle 20; c. 1.68 Ma), Beu (2001, p. 122) now recommends that the base of the Castlecliffian should be moved again to coincide with a slightly higher horizon, the eruption of the Ototoka Tephra (estimated age, 1.60 Ma; Beu 2001, p. 122). Both of these alternative new positions would contravene three paramount stratigraphic principles, those of historical priority (base-Castlecliffian at base Butlers Shell Conglomerate), of usage (almost 80 yr of consistent use), and of the time missing in an unconformity belonging by convention to the subjacent unit. Beu's (2001) recommendation also contravenes a fourth principle, of stability, because it discards without adequate justification the redefinition of base-Castlecliffian at the base of the Jaramillo Subchron (1.07 Ma) by Carter & Naish (1998), which has technical priority and was most carefully formulated to respect earlier usage.

It is a long-established principle in stratigraphy that where the base of a unit coincides with an unconformity, the "missing" interval belongs to the subjacent unit. For instance, Ager (1973, p. 71) pointed out that once a golden spike (GSSP) is defined "even if there is a break at the level chosen (i.e., an unconformity), the definition will stand and missing strata below the spike will automatically belong to the lower division". Similarly, McLaren (1977) notes that when a chronostratigraphic unit boundary is subsequently shown to lie "at a level of an undetected time break or hiatus, then the time missing would, by definition, belong to the (lower unit)". This view is perpetuated also in successive versions of the International Stratigraphic Guide (Hedberg 1976; Salvador 1994). Such strong and clear precedent precludes the redefinition of the base-Castlecliffian at the Ototoka Tephra, more than 300 k.y. below its traditional position and at a level within the Nukumaruan Stage that is not far above the boundary between the Hautawan and Marahauan Substages.

In justification of moving the base-Castlecliffian down to the level of the Ototoka Tephra, Beu remarks that to leave the boundary at its historic location (which is equivalent to the base-Jaramillo Subchron placement of Carter & Naish 1998) would result in "a succession of rocks containing undoubtedly Castlecliffian molluscs in the Rangitkei Valley ... languishing within the Nukumaruan Stage" (Beu 2001, p. 121). This revealing comment shows that Beu believes that the macrofaunal entities which he envisages for the Nukumaruan and Castlecliffian Stages exist independently of any formal stratigraphy or historical precedent. The facts of the matter are different, which is that the Rangitikei Valley beds referred to belong by definition in the Nukumaruan Stage, and the ranges of the "undoubted Castlecliffian molluscs" that they contain therefore extend well back into the Nukumaruan and, indeed, may well be useful indices for correlation of the Marahauan.

Nukumaruan: Carter & Naish (1998) specified the Matuyama/Gauss boundary as the LSSP for the base-Nukumaruan, with an estimated age of 2.58 Ma. This falls within MIS 103, about three obliquity cycles below the estimated MIS 97 age of the Hautawa Shellbed, which is the historic position for the base of the Nukumaruan Stage (Fleming 1953).

Beu (2001, p. 122) argues for moving the SSP back to its traditional position at the base of the Hautawa Shellbed, because it would then again coincide with the first occurrence of *Zygochlamys delicatula* in the Wanganui Basin. But, as Beu himself points out, the first appearance of this mollusc is highly facies dependent. *Zygochlamys* is also climatically controlled (Fleming 1944), known to have its first occurrence at markedly different times in different sedimentary successions (e.g., Beu 1969; Carter 2005), and may occur repeatedly within particular sections (e.g., Vella & Nicol 1970). For these reasons, and though its spasmodic occurrences are of great historic and continuing paleoclimatic interest, the use of *Zygochlamys* as an index fossil has long been set aside (e.g., Beu 1969).

I conclude not only that the LO of *Zygochlamys* is an unsatisfactory criterion on which to define an SSP, but that its use even in correlation is also questionable. Therefore, stratigraphic stability would best be served by allowing the revised base-Nukumaruan LSSP designation at the Matuyama/Gauss boundary to stand.

Waitotaran: Beu does not propose an LSSP for the Waitotoran because, despite its long historical standing, he recommends discontinuation of the stage (Beu 2001, p. 118). The base-Waitotaran therefore remains at the Gauss/Gilbert boundary with an estimated age of 3.60 Ma, as designated by Carter & Naish (1998).

Opoitian: Again, Beu (2001, p. 123) does not designate an LSSP for this stage, but suggests that one may eventually be nominated within the Wanganui River section. For the moment, then, the base-Opoitian remains at the base-Thvera Subchron with an estimated age of 5.25 Ma, as designated by Carter & Naish (1998).

Substages

Discontinuation of substages within the Castlecliffian and Nukumaruan: Beu (2001) gives an account of the historic reasons for which the substages of the Castlecliffian (the Okehuan and Putikian) and Nukumaruan (the Hautawan and Marahauan) were introduced by Fleming (1953). The published record is consistent with his suggestion that these four substages were intended to correspond broadly to the standard "four glaciations" model for the climatic history of the European Alps (cf. Penck & Bruckner 1909). Because the four-glaciation model is no longer current, and because of the lack of consistent macrofaunal indices by which the four substages can be characterised countrywide, Beu (1995, 2001 p. 120) recommends that they be dropped.

However, that the reasons for which it was introduced change or disappear has never been a sufficient argument for the discontinuation of a stratigraphic unit. Furthermore, since their introduction in 1953, the substages of the Castlecliffian and Nukumaruan have been used widely in the literature, and there are now many criteria other than macrofossils that can be used to identify them. The historic reasons advanced by Beu (1969, 1995, 2001) for discontinuing the substages are therefore not compelling and, indeed, have not been accepted (Vella & Nicol 1970; Carter & Naish 1998). It is for good reasons that a "do not change lightly" philosophy has always permeated stratigraphic classification.

The bases of the Okehuan and Hautawan Substages are defined by the same SSPs as the Castlecliffian and Nukumaruan Stages to which they belong (see above). Because he recommends discarding them, Beu (2001) does not nominate LSSP for the (upper) Putikian and Marahauan Substages. The designations of Carter & Naish (1998) for these substages therefore remain, with base-Putikian corresponding to the Brunhes/Matuyama boundary (c. 0.78 Ma) and base-Marahauan to the Pliocene/Pleistocene boundary. With respect to the latter, it can be objected that an LSSP should not be based upon an "overseas" criterion; indeed, such usage is effectively self-contradictory. Pragmatically, however, the Pliocene/Pleistocene boundary is approximated by the top of the Olduvai Subchron (c. 1.81 Ma), which like other magnetic reversals is a globally recognisable feature.

Substages of the Waitotaran: The substages of the Castlecliffian, Nukumaruan, and Waitotaran have lengths, from younger to older, of about: Wc (0.4, 0.3 Ma), Wn (0.7, 0.7 Ma), Ww (0.45, 0.45 Ma). The proposal to drop the Waitotaran and upgrade its constituent Waipipian and Mangapanian Substages to full stage rank, first made by Beu (1969) and reiterated by Beu (1978, 1995), uniquely introduced two full New Zealand stages with lengths less than c. 0.5 m.y. Beu's main justification for this change is that the biostratigraphic boundary between the Waipipian and Mangapanian "is one of the most easily recognised and reliable of (all) Wanganui Series boundaries" (Beu 2001, p. 118). Whilst it is true that there is a marked faunal change at the Waipipian/Mangapanian boundary, it is also the case that this change has been tested for homotaxy only, in addition to which there is a significant uncertainty in its numeric age. Finally, this faunal change is of course useful in its own right as an indicator of the boundary between the two substages, and upgrading them to full stage status does nothing to enhance their usefulness. When he first recommended upgrading the substages to full stages, Beu (1969, p. 643) noted that "a Waitotaran 'superstage' could still be usefully used where sections cannot be subdivided by means of key molluscs". That statement remains true to this day, except that the 'superstage' suffix is unnecessary.

Mangapanian: Beu (2001, p. 123) rejected Carter & Naish's (1998) designation of an LSSP for the Mangapanian Substage at the top of the Kaena Subchron (3.03 Ma), arguing, after Beu et al. (1987), that the base should revert to its traditional position (Fleming 1953)—the Mangapani Shellbed. The justification given for this is the presence in the shellbed of *Phialopecten* forms which are intermediate between the species *marwicki* and *thomsoni*, which Beu interprets as marking a speciation event. Alternatively, the *Phialopecten* morphology might be controlled by ecology, and the presence of the shellbed certainly demonstrates a facies and climatic influence also. It remains largely untested whether the *marwicki* to *thomsoni* change is (1) evolutionary or clinal, and (2) marks a New Zealand-wide time horizon or is simply homotaxial. Were Beu's recommendation adopted, the Mangapanian Substage would begin at the moment in time represented by the base of the Mangapani Shellbed (cf. Beu et al. 1987) and not (as indicated by GNS 2003) at the first appearance of *Phialopecten thompsoni*, for this taxon may later be found in a unit below the Mangapani Shellbed and will anyway probably have its first occurrences elsewhere at different moments in time. The base of the stage is defined by the rock reference, which is objective and permanent, and not by the presumed biostratigraphic indicator which, for a variety of reasons, may later change.

Recent research suggests that the base-Mangapanian (top-Kaena Subchron reversal) occurs near the top of the coastal section which crops out below the Mangapani Shellbed (Tim Naish pers. comm.), indicating that the LO of *P. thomsoni* in the shellbed is somewhat younger (c. 2.95 Ma) than has hitherto been estimated (3.03; Beu 1995, 2001). In the face of such uncertainty, it is unwise to use this probably partly facies-controlled macrofaunal change to define (as opposed to help correlate) the base of the Mangapanian, and at the same time to introduce two new stages, the boundaries of which have a numeric uncertainty that is of the same order as their length. Nothing is lost, and consistency of usage at least is gained, by maintaining the historical status quo, that is, by treating the Waipipian and Mangapanian as substages of the Waitotaran.

As for *Zygochlamys* and the base of the Nukumaruan, I conclude that the *Phialopecten* lineage change is not a particularly good criterion on which to base the definition of an SSP. Therefore, I recommend that the base-Mangapanian Substage should remain at the top-Kaena Subchron, at 3.03 Ma (Carter & Naish 1998). Beu himself noted (2001, p. 123), "the top of the Kaena Subchron is only slightly older than the base of the Mangapani Shellbed, so the position of the top of the subchron can be used as a convenient proxy for the stage boundary in other environments and localities where the *Phialopecten* lineage does not occur". This sums up exactly why Carter & Naish (1998) designated the LSSP for the Mangapanian in the top-Kaena position, and it is good to receive confirmation that—at least in marine rocks—the *Phialopecten* lineage may sometimes serve as an ancillary correlation criterion for recognising the boundary.

Waipipian: Beu (2001) does not designate an LSSP criterion for his upgraded Waipipian Stage, though he notes the future possibility of an SSP located in the Wanganui River section (Beu, 2001, p. 123). After Carter & Naish (1998), therefore, the base-Waipipian SSP corresponds to the base-Waitotaran SSP at the Gauss/Gilbert boundary (3.60 Ma).

Conclusion

Many of the matters discussed by Beu (2001) are relevant to improving the uncertain nature of New Zealand Pliocene-Pleistocene biostratigraphy, but not to matters of time-scale definition. Particularly unfortunate is his rejection of carefully formulated proposals for objective LSSP (Carter & Naish 1998), and their replacement mostly by biostratigraphic markers (GNS 2003).

The nomenclatural stability which results from according respect to designations made by earlier researchers is a *sine qua non* of stratigraphy. And especially so in the Pliocene-Pleistocene because of the variety of techniques now used for the correlation of such young strata, and the strong need for the researchers utilising these techniques to refer their disparate data to a common, objective rock standard. It has been clear at least since Vella & Nicol (1970) that radical changes to traditional Pliocene-Pleistocene stage usage in New Zealand should be avoided wherever possible. Such a presumption, and the parallel aim of maintaining the value of historic literature, underpins both the recommendations made by Carter & Naish (1998) and the additional comments made in this paper.