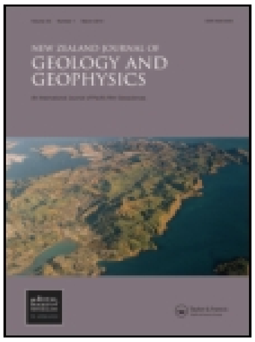

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New Zealand Journal of Geology and Geophysics

ISSN: 0028-8306 (Print) 1175-8791 (Online) Journal homepage: http://www.tandfonline.com/loi/tnzg20

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To cite this article: A. G. Beu (2001) Local stages to be used for the Wanganui Series (Pliocene-Pleistocene), and their means of definition, New Zealand Journal of Geology and Geophysics, 44:1, 113-125, DOI: 10.1080/00288306.2001.9514928

To link to this article: http://dx.doi.org/10.1080/00288306.2001.9514928

Published online: 23 Mar 2010.

New Zealand Journal of Geology & Geophysics, 2001, Vol. 44: 113–125
0028-8306/01/4401-0113 $7.00/0

Local stages to be used for the Wanganui Series (Pliocene–Pleistocene), and their means of definition

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Abstract Suggestions to abandon New Zealand local stages, or to redefine their boundaries solely at physically defined horizons, confuse the two very distinct aims of a stage classification. These are objectively to order New Zealand rocks on the basis of New Zealand biostratigraphic or other chronostratigraphic criteria, and to allow correlation of the New Zealand time-scale with the international one. For rapid, cost-effective identification of stages in geological mapping and other frontier situations, their boundaries must be characterised by biostratigraphic criteria, supplemented where appropriate by physical stratigraphic horizons (magnetic polarity reversals, sedimentary cycle boundaries, and, in particular, tephras).

Carter & Naish resurrected all Wanganui Series substages, but the original reasons for their proposal are outdated. Fleming's choice of subdivisions was governed by the "four glaciations" paradigm of the time, rather than the current Milankovitch time-scale paradigm. New Zealand Pliocene–Pleistocene stages need to be redefined at new stage-base boundaries (standard section and point, or SSP), at horizons that allow them to be characterised by the criteria of greatest utility in New Zealand.

Recommended stages and their SSPs (all sited in Wanganui Basin) are: Haweran Stage, base of Rangitawa Tephra (0.35 Ma), Rangitawa Stream, Rangitikei valley; Castlecliffian Stage, base of Ototoka tephra, Ototoka Beach, Wanganui; Nukumaruan Stage, base of Hautawa Shellbed, Hautawa Road, Rangitikei valley; Mangapanian Stage, base of Mangapani Shellbed, Mangapunipuni Stream, Waitotara valley. The SSPs for the Waipipian and Opoitian Stages need to be redefined using integrated molluscan, foraminiferal, and physical stratigraphic horizons in a continuous section in Wanganui Basin, preferably the Wanganui River section.

Keywords stages; biostratigraphy; Pliocene; Pleistocene; Wanganui Basin; magnetic polarity stratigraphy; cyclostratigraphy; tephrochronology; Mollusca

INTRODUCTION

The aim of stratigraphy is to determine the order of superposition of rocks, in order to display rocks on geological maps, to reconstruct basin history, and in general to determine the physical history of planet Earth. In areas of lithological and tectonic complexity, the critical criterion for superposition is the *age* of the rocks. A fundamental tenet of geology, therefore, is that geology is not comprehensible without knowing the age of the rocks.

But "age" in this context can refer to quite distinct concepts. The **relative** age of sedimentary rocks, allowing their comprehension at a level suitable for a particular region (e.g., within New Zealand), traditionally has been characterised by biostratigraphy based on the local biota. As pointed out by Carter & Naish (1998), New Zealand's isolation in the mid-latitudes of the Southern Hemisphere, and its consequently highly endemic biota, made a local biostratigraphy essential for determining the relative ages of rocks, particularly up until the 1980s. More recently, local biostratigraphy has achieved its greatest utility when zonations from different fossil groups are combined, and are integrated with physical stratigraphic horizons such as tephras and magnetic polarity reversals.

Long-distance correlation techniques are needed to place the local stratigraphy into a world context, and although this often will be achieved by techniques separate from local biostratigraphy, locally useful events in some groups (e.g., planktic foraminiferal and calcareous nannofossil extinctions and appearances) also can be internationally useful correlation events. **Numerical** ages now can be obtained by several techniques, and provide calendar ages of rocks, that is, in years. Numerical ages of rocks can be determined either within the local context or through correlation with well-dated successions outside the local region. Where tephras and/or sedimentary cycles are present, they provide invaluable visible, isochronous marker horizons that can assist biostratigraphy in determining stratigraphic position, and tephras can be dated independently to determine the numerical age of rocks. Sedimentary cycle boundaries are, of course, less useful than tephras for chronostratigraphy, as they provide a series of horizons that are not datable by themselves, and do not give a unique correlation solution; they must be calibrated by biostratigraphy. In theory, numerical ages of numerous tephras in a succession could determine relative ages and therefore superposition in the same way as biostratigraphy does. In practice, though, there are few places in the world with enough tephras in a succession for this to be practical, and such dating always will be more expensive and much more time-consuming than biostratigraphy. Integration of numerical ages and physical stratigraphic techniques with biostratigraphy provides a well-constrained result that is more useful than any of these methods by itself.

The New Zealand standard set of local (or regional) Cenozoic stages, defined by Finlay & Marwick (1940, 1947), has remained in use by most New Zealand geologists with only minor modification for more than 50 years. The

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Received 13 April 2000; accepted 11 October 2000

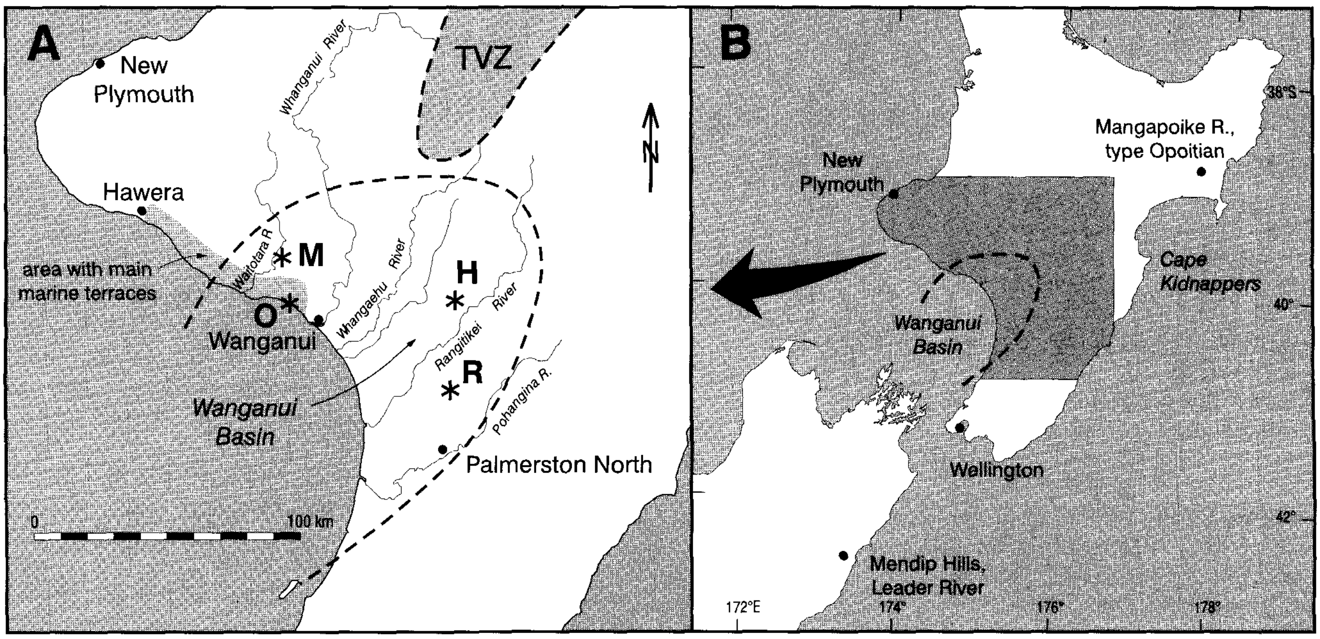

Fig. 1 Southwestern North Island (A) and central New Zealand (B), showing localities mentioned in the text. TVZ = Taupo Volcanic Zone (source of rhyolitic tephras in Wanganui Basin). Suggested locations of SSPs for stage boundaries are shown by lettered asterisks: H – Hautawa Road, Rangitikei valley (base Nukumaruan SSP); M – Mangapunipuni Stream, Waitotara valley (base Mangapanian SSP); O – Ototoka Beach, Wanganui coastal section (base Castlecliffian SSP); R – Rangitawa Stream, Rangitikei valley (base Haweran SSP).

approach of New Zealand biostratigraphers has been to accept these stages as the standard, and progressively to redefine them so as to retain the original set of stages with as little change as possible. Until very recently, their definition clearly has emphasised biostratigraphic criteria for their recognition. With the advent of other dating and correlation tools beside the original molluscan and foraminiferal biostratigraphy, the increased precision of stage definitions through integration of data from many techniques increasingly has shown boundaries to be poorly defined, or located at unsuitable horizons. It is my strong conviction that the answer to such problems of poor definition and poor choices of boundary position is not to abandon New Zealand local stages, or to redefine them at physically defined horizons, apart from a few (mainly tephras) that are particularly useful, visible, and clearly isochronous. Rather, I urge that the base boundary stratotype of each stage should be redefined at a single point identified in a single section (standard section and point, or SSP), and characterised by increasingly refined biostratigraphic criteria, integrated as closely as possible with physical stratigraphic methods. They then would follow the concepts and methods recommended in the International Stratigraphic Guide (Salvador 1994) and emphasised by the International Commission on Stratigraphy (Remane et al. 1996).

This paper sets out to clarify two separate points that have led in the past to unnecessary or confusing definitions of the Wanganui Series stages and substages. Firstly, it tempers the suggestions made by Carter & Naish (1998). These authors made a case for the eventual abandonment of New Zealand local stages, at least for the Pliocene and Pleistocene, and proposed new definitions of the boundaries of all the New Zealand Pliocene–Pleistocene stages and substages at physical stratigraphic horizons. I suggest a more moderate approach using the criteria of most use within New Zealand, in particular a combination of tephras (visible, isochronous, physical stratigraphic horizons) with biostratigraphy. Secondly, I will show that Fleming (1953) defined substages of the Nukumaruan and Castlecliffian Stages on inadequate biostratigraphic grounds because he tried to fit them to the "four glaciations" paradigm developed in Europe. The stages and substages of the Wanganui Series deserve to be reconsidered in the current Milankovitch timescale paradigm, to produce the stage subdivision of most use within New Zealand. Sections within Wanganui Basin and localities mentioned in the text are shown in Fig. 1.

Abbreviations: Abbreviations used throughout this paper are: HO, highest occurrence (recommended rather than "last occurrence"); ITPFT, isothermal plateau fission track date, or dating method; LO, lowest occurrence (recommended rather than "first occurrence"); Ma, millions of years ago (applied only to numerical dates); m.y., million years; OIS, oxygen isotope stage—numbered oscillations in the oxygen isotope curve derived from deep-sea cores, that is, alternating glaciations (even-numbered stages) and interglacial periods (odd-numbered stages); SSP, standard section and point—a designated point in a designated section, defining the boundary stratotype of a stage; for stages of the global standard succession, these are labelled GSSP.

DEFINITON OF NEW ZEALAND STAGE BOUNDARIES SHOULD USE THE CRITERIA OF GREATEST UTILITY WITHIN NEW ZEALAND

The case made by Carter & Naish (1998) for the abandonment of New Zealand stages was based on the premise that worldwide Pliocene–Pleistocene rocks now are exceedingly well correlated by the "new" techniques such as cyclostratigraphy, by its corollary of astronomically derived numerical dates, by magnetic polarity stratigraphy, by stable isotope stratigraphy, by tephrochronology, and by numerical ages. The correlation between New Zealand Pliocene–Pleistocene rocks and those of the standard succession supposedly is tightly enough constrained that we can abandon the New Zealand stages, and use the standard succession of stages to classify New Zealand rocks. (The biostratigraphically characterised stages of western and southern Europe are accepted as constituting the international standard Cenozoic time-scale.) Carter & Naish (1998) then went on to suggest that, if local stages are to be retained for Pliocene–Pleistocene rocks in New Zealand, they should be redefined at physical stratigraphic horizons. They considered that physical horizons (including magnetic polarity reversals) more easily were correlated with the international standard succession than are the biostratigraphic extinction and evolutionary events in use at present. They nominated (Carter & Naish 1998, fig. 1) a set of physical horizons to define the New Zealand local Pliocene–Pleistocene stages. Most of these horizons are magnetic polarity reversals, but they include one tephra (Rangitawa Tephra, 0.35 Ma, defining base Haweran Stage) and the Pliocene/Pleistocene boundary (which merely is one of the many Pliocene–Pleistocene sequence boundaries, of no geological significance within New Zealand).

To establish my approach to the definition of New Zealand Pliocene–Pleistocene stages, I list here the basic points that I consider need to be kept in mind when establishing a local chronostratigraphic classification.

1. *Chronostratigraphic subdivision in New Zealand initially used biostratigraphic criteria.* Clearly, as none of the physical stratigraphic methods recommended by Carter & Naish (1998) was in use when chronostratigraphic subdivision began here, no method other than biostratigraphy was available at the time. This gives biostratigraphy the great advantage of a long period (135 years in New Zealand, to date) of iterative comparisons of different criteria to develop an accurate time-scale that, by now, largely has weeded out any diachronous and otherwise unreliable taxa.
2. *Local stages are intended for local use.* Local stages were needed in New Zealand because of its highly endemic biota, and the consequent inability to make use of the European (or any other) biota to subdivide New Zealand Cenozoic rocks. This remains as true now as in the past. The scheme of local stages developed in New Zealand is highly useful for identifying ages of New Zealand rocks, at the stage time-scale (c. 1–5 m.y. per unit). It has proved its worth for mapping and other uses within New Zealand where chronostratigraphic subdivisions of New Zealand rocks are needed for the local geology to be understood. New Zealand stages were not intended to be tools for international correlation or for the accurate determination of geological and other rates and processes. An accurate calendar scale is, of course, needed to determine rates, and is being achieved with radioisotopic dating techniques and with international correlation using the physical stratigraphic methods applauded by Carter & Naish (1998). The local stages always will remain useful for geological research within New Zealand, and research will continue to refine their biostratigraphic characterisation in order to use the most reliable possible criteria for their recognition.
3. *There are no inherent differences between European stages and New Zealand ones.* Carter (1970, 1974) and Carter & Naish (1998) claimed that the lack of formal stage definitions, each citing a single criterion at a point in a stated section, demonstrates that the New Zealand local stages actually are oppelzones. It should be realised, though, that the type of stage definition formerly used in New Zealand is no different from that used in western Europe to define Cenozoic stages. The western European local stages now are accepted as the world standard Cenozoic time-scale, but, apart from those that now have been redefined by GSSPs, there is nothing inherently different about them from those in use in New Zealand.
4. *Biostratigraphic subdivision of rocks is easier and much more rapid, and so much more cost effective, than physical stratigraphic methods.* Physical stratigraphic methods (particularly magnetic polarity stratigraphy, radioisotopic dating methods, and chemical identification of tephras) are too specialised and too time-consuming to be applied in frontier situations. Biostratigraphic characterisation of stages always will be needed for geological mapping, estimating ages of newly discovered remote outcrops, and, in particular, defining stratigraphic progress during the drilling of wildcat oil wells from which drill cuttings are the only samples available. No physical stratigraphic method can replace biostratigraphy for local correlation of Cenozoic rocks in these situations in the foreseeable future.
5. *Some physical stratigraphic methods produce an ordered but undated "bar code" that must be calibrated with the time-scale by means of biostratigraphy.* This particularly applies to cyclostratigraphy and magnetic polarity stratigraphy. These methods do not produce a unique solution by themselves.
6. *Some visible physical stratigraphic markers inherently are isochronous, and so provide the most useful possible criteria for the chronostratigraphic subdivision of Cenozoic rocks*—most notably tephras and, in well-dated cyclic successions, depositional sequence boundaries. Obviously, chronostratigraphy will be improved by combining such methods with biostratigraphy. However, tephras are far from ubiquitous, even in New Zealand, and they will not be useful as generally through the stratigraphic column as biostratigraphic evolutionary and extinction events are. They are much more common in some parts of the stratigraphic column than others, and their preservation in a particular basin partly depends on the prevailing wind at the time of eruption. Tephras do have one compelling advantage over biostratigraphic criteria, though; their airfall origin allows correlation in and between both non-marine and marine basins. For some tephras, it also allows recognition in deep-sea cores around New Zealand beyond the range of a single set of biostratigraphic criteria. Within Wanganui Basin, tephras are highly useful for chronostratigraphy of late Pliocene and Pleistocene rocks, and their usage will continue. However, few will be useful in New Zealand in rocks older than late Pliocene.
7. *Stage boundaries have been selected at major, obvious biotic events.* The succession of molluscan faunas in

the late Neogene in New Zealand consists of a sequence of distinctive step-wise faunal changes, and stage boundaries have been selected at the horizons of significant generic turnover (Beu 1990). This is not intended to imply that all biotic change occurred at these steps, merely that a considerable portion of it did (>50% in most cases). The most easily recognised of these steps is the Nukumaruan/Castlecliffian Stage boundary, which is characterised by a major faunal extinction event. At least 21 genera of molluscs became extinct in New Zealand during Nukumaruan time, and 13 of these became extinct at the end of Nukumaruan time. These are large, common, easily identified molluscs (*Glycymeris* (sensu stricto), *Towaipecten*, *Panis*, *Patro*, *Pteromyrtea*, *Pseudocardium*, *Spisula*, *Lutraria*, *Zenatia* (*Zenatraria*), *Marama*, *Eumarcia*, *Atamarcia*, and *Taxonia*). Molluscan faunas allow easy, rapid recognition of stages in the widespread shallow-water facies that are most common on land during this period. Molluscs also have the great advantage over all other criteria of being usable in the field instantly, without any recourse to laboratory techniques. In my opinion, it would be unfortunate and inappropriate to ignore this easy, readily available means of chronostratigraphic subdivision of New Zealand Pliocene–Pleistocene rocks.

8. *The base stratotypes of New Zealand stages are to be redefined at SSPs.* New Zealand practice is to follow the recommendations of the International Stratigraphic Guide (Salvador 1994) and the Commission on Stratigraphy's guidelines for the establishment of chronostratigraphic units (Remane et al. 1996) in the establishment and maintenance of a chronostratigraphic classification. Aubry et al. (1999) have pointed out difficulties resulting from the strict adherence to these principles in some cases (particularly with the definition of the Eocene/Oligocene and Paleocene/Eocene boundaries), but these do not remove the necessity for international co-operation and uniformity in the definition of stratigraphic units. The international guides state explicitly that stages are to be defined by their *lower* boundary stratotype, the designated point at which a nominated biostratigraphic criterion or physical stratigraphic horizon occurs in a designated section (an SSP). This boundary automatically defines also the top of the underlying stage. A significant emphasis of the Foundation for Research, Science and Technology funded Time-scale Project being carried out by the Institute of Geological & Nuclear Sciences is to redefine New Zealand local stage boundaries at SSPs in designated sections, so that they can be characterised by appropriate biostratigraphic and physical criteria. Any criticism of the means of definition of the New Zealand chronostratigraphic classification then will be unfounded.

9. *A chronostratigraphic classification has at least two separate aims.* In my opinion, the statements and definitions by Carter & Naish (1998) fail to distinguish between the (at least) two discrete aims of a local chronostratigraphic classification:

   a. it is a tool for ordering local strata and events, for mapping and basin analysis, and, perhaps most economically important, for determining stratigraphic progress in oil wells;

   b. it is a tool for correlating the ordered local strata with the international time-scale, in order to be able to calibrate geological and evolutionary rates and processes, and for international communication. This second aim also is carried out in part by numerical dating of the local succession.

10. *Objective establishment of a local chronostratigraphic scale should precede international correlation.* The great problem with the New Zealand local Pliocene–Pleistocene stages as redefined by Carter & Naish (1998) is that they satisfy only the second aim listed above—long-distance correlation. They completely ignore the primary aim—subdivision and ordering of New Zealand rocks by New Zealand criteria. The objective approach to chronostratigraphy is first to establish a local time-scale using New Zealand criteria, and only secondly to correlate this local time-scale with the international one.

11. *Visible horizons are more useful than invisible ones for defining stage boundaries.* Both tephras and biostratigraphic criteria (particularly molluscan faunal changes) are considered to be "visible" here, as are sedimentary cycle boundaries. Magnetic polarity reversals not only identify invisible horizons but also are very specialised and time-consuming to identify. They definitely are less desirable criteria than visible horizons for the practical identification of local chronostratigraphic boundaries.

12. *The most flexible, reliable, and objective time-scale would use an integrated combination of all available dating and correlation techniques.* Bearing in mind all the points listed above, this combination initially would take into account only the degree of utility of a stratigraphic criterion *within New Zealand*. Some account possibly might be taken later of internationally useful correlation criteria, but this criterion is of little or no significance for the establishment of a *New Zealand* time-scale.

Subdivision of New Zealand rocks

The first and much the more significant aim of local stages, as far as the New Zealand geological community is concerned, is to provide an ordered subdivision of New Zealand rocks, largely characterised by local biostratigraphy. Carter & Naish (1998) themselves pointed out that the greatest advances came in the subdivision and mapping of New Zealand Cenozoic rocks when H. J. Finlay was able to use newly defined local foraminiferal biostratigraphy to subdivide the enormous thickness of monotonous Cenozoic mudstone that had not been divisible previously. Local stages always will be required in all parts of the world with fossiliferous sedimentary rocks, using the local biostratigraphy and any helpful physical stratigraphic horizons for their recognition. Local biostratigraphy is by far the most rapid and cost-effective method of subdividing rocks in "frontier" applications. As stated pragmatically by Hornibrook (1965, p. 1210), there always will be a need for "the rocks and fossils on which we base our classification [to] be accessible to the hammers of New Zealand geologists". The suggestions by Carter & Naish (1998)

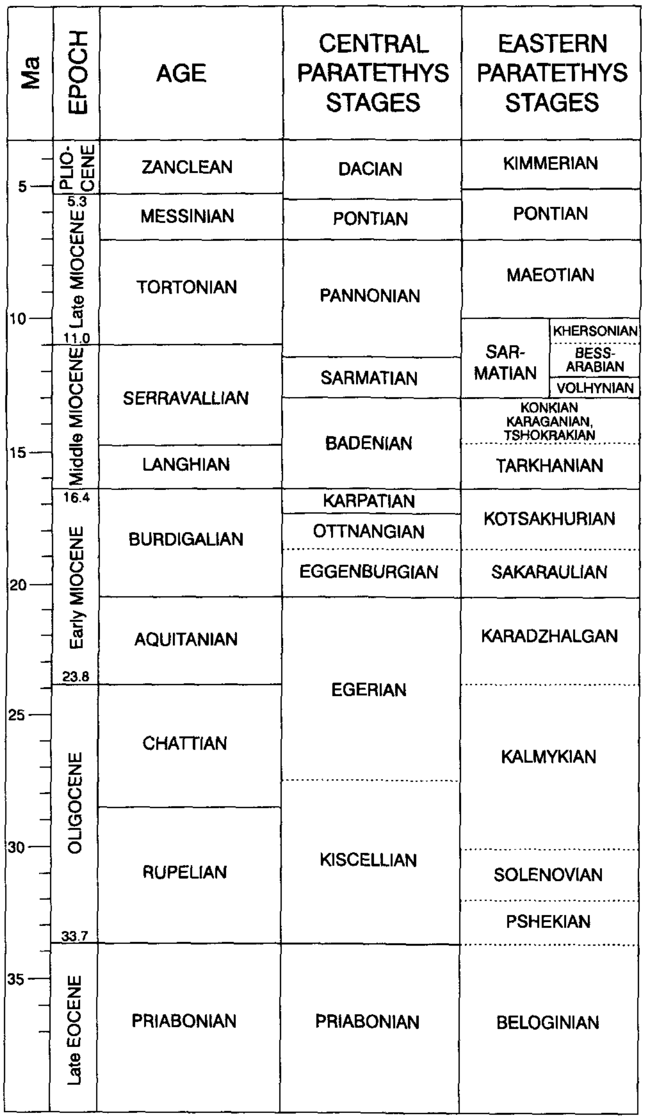

Fig. 2 Stages in use for the Oligocene and Neogene of Europe (redrawn from Rögl 1998, table 1), with right column deleted ("biozones", from Berggren et al. 1995).

demonstrate remoteness from the routine, day-to-day servicing of field geologists and well drillers, that is, from all but the most academic members of the geological community.

A concrete example of the utility of local stages is provided by the three separate successions of Cenozoic local stages in parallel use in Europe (Rögl 1998, table 1) (Fig. 2) and increasingly refined in recent years. One of these successions, in use for western Europe, is the accepted international time-scale. The others are used to subdivide rocks geographically much nearer to western Europe than New Zealand is. Nevertheless, the two other successions of local stages are necessary to subdivide the rocks of central and eastern Europe, because many species that provide the biostratigraphic criteria used to characterise the stages are endemic to relatively small basins in Europe.

Long-distance correlation

In contrast, long-distance correlation of the New Zealand time-scale with the international one increasingly is being refined by the non-biostratigraphic methods claimed by Carter & Naish (1998) to render biostratigraphically characterised stages irrelevant. Methods such as magnetic polarity stratigraphy, cyclostratigraphy and its astronomical calibration, and the various physical dating and stable isotopic techniques are without doubt of the highest utility for refined correlation of New Zealand rocks with those outside New Zealand and for providing numerical dates.

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. Even then, though, the local biostratigraphy still would be required for the recognition and correlation of these stages within New Zealand, at least for periods when the local biota is highly endemic. However, the high degree of endemism of the New Zealand Cenozoic biota means that there is little real prospect of such a level of precision being achievable for Cenozoic stages.

In summary, I emphatically defend the need for New Zealand local stages identified objectively by the most useful New Zealand biostratigraphic or physical stratigraphic criteria, but defined formally in designated sections by SSPs that tie each stage boundary unambiguously to a horizon in rocks. The most widely, rapidly, and cheaply useful criteria to characterise stages always will be biostratigraphic ones, but some physical stratigraphic horizons also are useful. Tephras are visible, physical, isochronous stratigraphic horizons that provide a particularly useful adjunct to biostratigraphy in some areas of New Zealand (e.g., Wanganui Basin; Alloway et al. 1993). The use of tephras as stage boundary criteria would make the recognition of stages simple and would be particularly appropriate in Wanganui Basin, with its many rhyolitic tephras. [The danger should be borne in mind, though, that if a tephra were used as the recognition criterion for a stage boundary, the criterion would not be present in basins where the tephra was not deposited.] The objective, scientific approach to chronostratigraphy is first to define the local biostratigraphic criteria and zonation to compile an objective time-scale, with the aid of helpful physical stratigraphic horizons where they are available and are suitably widespread, and then to correlate the local time-scale with the international one. The "local" stages defined purely at physical stratigraphic horizons by Carter & Naish (1998) are of no use for the routine recognition of subdivisions of New Zealand rocks, and must be rejected. A more objective approach using all possible criteria is recommended, keeping in mind the 12 significant points advanced above, to arrive at the classification most useful for the New Zealand geological community. Correlation with the international time-scale should remain a separate, later discipline independent of whatever New Zealand time-scale is adopted. Eventually, correlation of the entire New Zealand Neogene succession could well be possible at the scale of individual oxygen isotope stages, and this would provide the ideal subdivision of the local stages for particularly detailed geological purposes.

SUBSTAGES OF NUKUMARUAN AND CASTLECLIFFIAN: GOVERNED BY THE "FOUR GLACIATIONS" PARADIGM

This section is included to make it clear why I consider the substages of the Nukumaruan and Castlecliffian Stages to be unfortunate concepts of little significance in New Zealand geology.

Historical background

The historical background to the recognition of the stages of the Wanganui Series was outlined by Fleming (1953, pp. 97–100; 1959, pp. 63–65). Almost all these stages were defined in Wanganui Basin, in southeastern North Island. The exception is the earliest Pliocene stage, Opoitian, which was defined loosely by Finlay (1939, p. 530) in Mangapoike River, northern Hawke's Bay, in the central eastern North Island. The Castlecliffian and Waitotaran Stages were defined by Thomson (1916, p. 36) in the section exposed along the Wanganui–South Taranaki coast. The Nukumaruan Stage was added to this succession by Marwick (1924, table p. 127) who, rather than using Thomson's two stages, recognised the Waipipian, "Nukumaruian", and Castlecliffian Stages as subdivisions of the "Wanganuian [Series]". Fleming (1953) did not redefine any of these stages more closely, as he identified only a type formation and locality for each stage, deliberately leaving room for changes in the boundary position. Wanganui Series local Cenozoic stages never have been defined in a formal sense with anything like the rigour demanded by the International Stratigraphic Guide.

Subdivision of most of the Wanganui Series stages was proposed by Fleming (1953, pp. 102–103). He proposed that the Waitotaran Stage be subdivided into the Waipipian (lower) and Mangapanian Substages, the Nukumaruan Stage be subdivided into the Hautawan (lower) and Marahauan Substages, and the Castlecliffian Stage be subdivided into the Okehuan (lower) and Putikian Substages. In Fleming's classification, a Hawera Series separated the Castlecliffian Stage from the Recent or Holocene. Some later authors (Fleming 1962, p. 82; 1975a, 1979; Vella 1963, p. 38) have recognised all Fleming's substages as full stages and adopted the earlier name for the younger stage in most cases, that is, they recognised the Waipipian, Waitotaran (or Mangapanian), Hautawan, Nukumaruan, Okehuan, and Castlecliffian Stages. Others have sought a more objective compromise, recognising as stages those subdivisions that unambiguously can be recognised over much or all of New Zealand, and downplaying subdivisions (particularly Hautawan and Okehuan) that are of low biostratigraphic reliability. On the basis of molluscan biostratigraphy, the Waipipian/Mangapanian stage boundary is one of the most easily recognised and reliable of Wanganui Series boundaries (more easily recognised, for example, than the Opoitian/Waipipian boundary). These therefore consistently have been recognised by most biostratigraphers as full stages in place of the former Waitotaran Stage. In contrast, subdivisions of the Nukumaruan and Castlecliffian Stages have not been used by most biostratigraphers in recent years (Beu et al. 1987; Hornibrook et al. 1989, fig. 6; Beu & Maxwell 1990, fig. 2; Scott et al. 1990, fig. 1; Beu 1995, fig. 1; Crampton et al. 1995; Morgans et al. 1996; Naish et al. 1998, fig. 4). It, therefore, was surprising to see all the substages, and even the Waitotaran Stage, resurrected by Carter & Naish (1998).

Fleming's stage classification and the "four glaciations" paradigm

In order to reveal the underlying reasons for the subdivisions Fleming (1953) recognised for the younger stages of the Wanganui Series, it is necessary to take into account the "four glaciations" paradigm ruling at the time. Fleming carried out his fieldwork during 1945–48 (Fleming 1953, p. 1) and wrote the bulletin shortly afterwards, at the time when the "four glaciations" of Europe provided the unquestioned paradigm governing the interpretation of Pleistocene rocks. This was long before the paradigmatic shift, commencing in the 1970s, to the frequent, relatively brief, glacial/interglacial oscillations of the "Milankovitch time-scale" Pliocene–Pleistocene that are taken for granted now (e.g., Pillans et al. 1998). Indeed, Milankovitch was thought of at the time as misguided, at best.

The important clue to Fleming's interpretation of the glacial/interglacial succession in Wanganui Basin is hidden away within his text. Fleming (1944) already had pointed out the paleoclimatic significance of the cold-water scallop *Zygochlamys delicatula* (Hutton), interpreting its appearance in the central North Island as the result of a late Pliocene cooling event. Fleming (1953, p. 126) expressed clearly, for the first time, his concept that the abrupt appearance of *Z. delicatula* in the central North Island equates with the recognition in Europe and Britain of the base of the Pleistocene "at the horizon of the first indications of climatic deterioration in the Italian Neogene succession". This led, from about 1956 on, to the identification of the base of the Nukumaruan Stage as the base of the Pleistocene in New Zealand. Fleming (1953, p. 126) noted that "there is no indication that such early glaciation, in the middle of the Wanganui Epoch, preceded the earlier glaciations of other parts of the world, some of which were once attributed to the Pliocene" (e.g., Pilgrim 1945).

Fleming (1953) identified and mapped only two uplifted Pleistocene marine terraces (comprising the Hawera Series) along the Wanganui–South Taranaki coast, of the 13 later recognised by Pillans (1983, 1990). These apparently represented only two glacial/interglacial cycles. Having identified the commencement of the "Hautawan" glaciation with the base of the Pleistocene, Fleming was left with identifying the remaining one cool period and two warm periods required to satisfy the paradigm of four Pleistocene glaciations. He made several references to the "cool-water" or "warm-water" nature of the faunas of the substages of the Nukumaruan and Castlecliffian Stages. Although there is no clear statement of this concept in the bulletin (Fleming 1953), these were regarded as two pairs of alternating cool and warm periods, provided with their own substages in the manner then becoming standard for the British Pleistocene succession.

By 1978, Fleming (in Suggate et al. 1978, pp. 556–563; it should be realised, though, that much of this book was written up to 10 years before it was published) had a more complex concept of the glacial/interglacial succession at Wanganui. However, he still followed the "four glaciations" paradigm, despite referring to the Kai-Iwi Group as "a series of cyclothems" (Fleming in Suggate et al. 1978, p. 562). A few quotations from this review demonstrate Fleming's interpretation: "Nukumaru Group macrofaunas ... include several warm-water forms, so that they are inferred to be deposits of *the first interglacial*" (p. 559); "Okehuan faunas are impoverished ... These deposits ... may be interpreted as the first of *a transgressive interglacial sea*, during the early part of the *glacio-eustatic rise of sea-level following the second glacial period* of Wanganuian time" (p. 561) (italics mine).

In a review for the International Quaternary Association congress held in Christchurch in 1973, Fleming (1975b) still adhered to the "long time-scale" paradigm, despite the fission-track and other numerical dates then becoming available (it is clear from the context that this review postdates that published in Suggate et al. 1978). Fleming (1975b, p. 4) again referred to the Castlecliffian succession in the Wanganui coastal section as "a thick sequence of at least a dozen cyclothems suggesting glacio-eustatic cycles". However, he underplayed the significance of the frequent diastems, noting that "the abundant faunas ... are of generally warm temperate facies and deposition remained marine so that *no further glaciation is indicated*" (italics mine). In his conclusion, "Chronology", Fleming (1975b, pp. 17–18) realised the correlation and chronological problems that were beginning to arise through adherence to the long time-scale paradigm, and wondered "Do the cyclothems represent interstadial sea-level fluctuations?" Only the Milankovitch time-scale paradigm was to provide the answer.

It is clear, then, that Fleming (1953) interpreted the Pleistocene Epoch as commencing in New Zealand with the cold Hautawan Substage (corresponding to a glaciation, correlated with the Ross Glaciation recognised in the western South Island by Gage 1945) (Fleming 1953, p. 126). This was followed by the warm Marahauan interglacial period, followed by the cool Okehuan glacial period, followed by the warm Putikian interglacial period, followed in turn by the two glacial/interglacial cycles recognised in "Hawera Series" time.

As pointed out below, the bases of Wanganui Series stages recommended below (Opoitian, Waipipian, Mangapanian, Nukumaruan, and Castlecliffian Stages) are recognised easily in relatively shallow water facies by significant generic turnover of the molluscan fauna (Beu 1990). In contrast, the substages proposed by Fleming (1953) are identified by only relatively few changes at the species level, many of which probably could not be recognised outside Wanganui Basin. The substages are poorly characterised, biostratigraphically. Fleming's view of the faunal recognition of the substages of the Nukumaruan and Castlecliffian Stages apparently was coloured by a few striking occurrences of warm-water molluscs, but the passage of time has lessened their significance. The molluscs present within one cycle are affected by accidents of paleogeography, which switched on or off the northern or southern molluscs able to reach Wanganui Basin as planktonic larvae in currents passing through the gaps in the axial mountain chain. They also are affected by differences between the depths of deposition of the highstand units of different cycles (fewer apparently "warm-water" taxa being present in deeper water facies than in shallower ones), and by the near-random appearance of dispersalist molluscs in New Zealand from Australia during interglacial periods. These factors now are seen to explain molluscan distributions that were assumed by Fleming (1953, 1957) to result from significant climatic differences within New Zealand, affecting the faunas of the substages.

It appears, then, that the perceived need to identify the "four glaciations" of Europe in the New Zealand succession coloured Fleming's choice of subdivisions of the Wanganui Series, to the extent that he (unconsciously) overstated the weak biostratigraphic distinctions between the substages. This control on the recognised subdivision exerted by the "four glaciations" paradigm is seen as overly simplistic now, of course, in the current paradigm of the Milankovitch Pleistocene time-scale, with its numerous, frequent glacial/interglacial oscillations. The stages and substages used in New Zealand deserve to be reconsidered, on the basis of rigorous biostratigraphy integrated with all other possible techniques, independently of climatic interpretations and of possible correlations with the international time-scale.

It is equally clear, though, that we need to be aware of the influence of the ruling paradigm, and not be overly influenced by current paradigms (such as sequence stratigraphy and the Milankovitch time-scale) in our choice of stratigraphic subdivisions. To some extent, it could be said that striving for international correlation, rather than arriving at an independent subdivision based on New Zealand criteria, led to Fleming's recognition of unhelpful substages.

RECOMMENDED STAGES AND BOUNDARY CRITERIA

This final section recommends local stages to be recognised in New Zealand for the later Wanganui Series, based on physical stratigraphic horizons that are in helpful positions, on my knowledge of the molluscan biostratigraphy, and on the points at which boundary stratotypes might most usefully be defined. Further research is required before SSPs for the recognised stages actually are designated, and this will be the subject of later papers.

Use of molluscan biostratigraphy

A point deserving emphasis here is the continued characterisation of the stages of the later part of the Wanganui Series largely by molluscan biostratigraphy. This is discussed also under point (7) in the list above. Mollusca certainly have to be used with care in biostratigraphy, as their enormous diversity (>5000 species; Beu & Maxwell 1990) results from many species inhabiting more narrowly restricted environments than most microfossils do. However, it is still true that molluscs remain the most useful fossils for the subdivision of Pleistocene and later Pliocene rocks, where nearshore facies are very widespread and molluscs are common and diverse. In shallow facies of Pliocene age, particularly limestone, pectinids provide the most reliable biostratigraphy (Beu 1995). In Nukumaruan–Haweran Stages (latest Pliocene–Pleistocene), little other than nearshore facies are preserved on land. During this period, molluscs are abundant and diverse, and few microfossil events are useful for biostratigraphy. Also, a large amount of research over 135 years has resulted in a detailed molluscan biostratigraphy for this period (Fleming 1953; Beu & Maxwell 1990, fig. 5–7; Beu 1990, 1995). Molluscan index taxa will continue to provide the primary biostratigraphic criteria of the Mangapanian, Nukumaruan, Castlecliffian, and Haweran Stages, along with a few of the most useful physical stratigraphic horizons. Molluscs also always will be useful for recognising stages in shallow facies of at least late Oligocene to mid-Pliocene age (Duntroonian–Waipipian Stages). In the following section, molluscan events are recognised as the most useful biostratigraphic criteria for identifying stages in New Zealand late Pliocene–Pleistocene rocks, and are combined with suitable physical stratigraphic horizons to define stages useful to the New Zealand geological community.

Are Nukumaruan and Castlecliffian substages useful?

I pointed out above that Fleming (1953) proposed the substages of the Nukumaruan and Castlecliffian Stages for reasons that now are not seen as helpful. The most useful biostratigraphic criterion for the Hautawan Substage, the LO in central New Zealand of the cold-water *Zygochlamys delicatula* fauna, had a limited geographic expression (Beu 1969). All Nukumaruan rocks of North Canterbury contain *Z. delicatula*, whereas none do in northern Hawke's Bay. Also, Beu (1999) showed that *Z. delicatula* reached as far north as the Three Kings Islands, north of the northernmost North Island, at least briefly during the last glacial maximum. *Z. delicatula* is a readily dispersed but highly facies dependent fossil whose HO seems to be highly unreliable for biostratigraphy. We know now that its LO also probably varied in age from basin to basin, because of the different expression in different basins of the low deposition rate facies it requires (Orpin et al. 1998). However, its appearance in the central North Island remains one of the most dramatic faunal events in New Zealand geological history. Its LO in Hautawa Shellbed in Wanganui Basin still provides a useful basal criterion for the Nukumaruan Stage (in OIS 98; Naish et al. 1997, 1998; Carter & Naish 1999), and this position can be identified in other basins by microfaunal and palynological correlation. The lack of the *Z. delicatula* fauna in higher Nukumaruan strata of Wanganui Basin was the sole criterion for distinguishing the Marahauan Substage, and this now appears to be an inadequate reason to subdivide the Nukumaruan Stage.

Fleming (1953) based the distinction between the Okehuan and Putikian Substages primarily on the LO of *Pecten* at the base of Putikian, as he knew it, that is, at the base of Kupe Formation in the Castlecliff coastal section. Soon afterwards, P. Vella collected an abraded specimen of *Pecten* (Fleming 1957, p. 30) lower in the section, from what is now named Upper Westmere Shellbed (Abbott & Carter 1999). *Pecten* since has been collected at this lower horizon at several other localities in Wanganui Basin. Although the substage boundary never has been formally moved downwards to the base of Upper Westmere Shellbed, it should be moved down if the LO of *Pecten* is to be used as the main recognition criterion for Putikian. Also, the lower position usefully coincides almost exactly with the Brunhes/Matuyama magnetic reversal (Turner & Kamp 1990), dated at 0.78 Ma (Bassinot et al. 1994). It might seem at first sight, then, that the definition of the Okehuan/Putikian Substage boundary at the Brunhes/Matuyama reversal by Carter & Naish (1998) was a sensible idea, and that the LO of *Pecten* could be used as a biostratigraphic proxy for the reversal.

Unfortunately, though, the LO of *Pecten* has no biostratigraphic significance in the wider New Zealand context. Both at Cape Kidnappers, southern Hawke's Bay (P. J. J. Kamp, University of Waikato, pers. comm.; Black 1992), where it is present in Maraetotara Formation, and at Mendip Hills, Leader River, North Canterbury (Warren 1995, fig. 21), fossiliferous rocks containing *Pecten* underlie Potaka Tephra. This tephra is dated at 1.05 Ma (Shane 1994; Shane et al. 1996), so it is clear that *Pecten* appeared in eastern New Zealand more than 1 m.y. ago, well before its first occurrence in Wanganui Basin (shortly after 0.78 Ma).

Subdivision of the Castlecliffian Stage, also, clearly was based on unreliable biostratigraphic criteria. Subdivision of Nukumaruan, Castlecliffian, and Haweran time seems best carried out at the OIS level, and in my opinion recognition of the Hautawan, Marahauan, Okehuan, and Putikian Substages is undesirable.

Suggested SSPs

Beu et al. (1987, fig. 2) provided a table of stage definitions for the bases of the Wanganui Series stages in New Zealand, essentially defining (informally) the SSPs for these stages. However, not all these positions now are seen as appropriate. The SSP positions are listed here that seem most suitable to me, bearing in mind local biostratigraphy, the suggestions by Carter & Naish (1998), the 12 points listed at the beginning of this paper, and the requirements of the International Stratigraphic Guide. Figure 3 provides a comparison between the subdivisions suggested by Carter & Naish (1998) and those recommended here.

Pillans (1983, 1990) identified a suite of 13 uplifted marine terraces along the Wanganui–South Taranaki coast, at least six of which overlap in age with the Castlecliffian Stage as recognised by Fleming (1953). These terraces form the "Hawera Series" as recognised by Thomson (1917) and Fleming (1953). Vella (1972, table 1), Fleming (1975b, p. 15), Grant-Taylor & Te Punga (in Suggate et al. 1978, pp. 551–552), and Beu et al. (1987) pointed out that "Hawera Series" partly was coeval with Wanganui Series, and so Beu et al. (1987) deleted Hawera Series from the New Zealand succession. They proposed the Haweran Stage (within Wanganui Series) to extend from the end of Castlecliffian time until the present day. The boundary between Castlecliffian and Haweran Stages was provided with a biostratigraphic definition by placing it at the top of Putiki Shellbed in its type section, on the river road at Putiki, east of Wanganui City. This boundary was defined by the apparent extinction horizon of the *marwicki* form of *Pecten novaezelandiae*.

Recommended stages and their SSPs for the Wanganui Series are as follows:

1. Haweran SSP: The position identified above, at the top of Putiki Shellbed on the river road east of Wanganui, still seems the best position for a Haweran SSP characterised by biostratigraphic criteria. At this level, the base of the stage is identified biostratigraphically by the HO of *Pecten novaezelandiae* form *marwicki*. However, there are very few other criteria that could be used for biostratigraphic subdivision this high in the column, that is, few other molluscan or microfossil criteria support the characterisation by the HO of *P. novaezelandiae* form *marwicki*. Also, this form of *P. novaezelandiae* is of little significance for taxonomy, ecology or, probably, biostratigraphy in the wider New Zealand context, as it has not been recognised outside Wanganui Basin. A physical stratigraphic horizon seems likely to provide a more readily identifiable stage boundary marker than a biostratigraphic one in rocks this young. The horizon suggested by Carter & Naish (1998) to identify this stage boundary, Rangitawa Tephra, therefore is agreed to be the most useful. The tephra is well dated by both zircon fission-track dating and ITPFT dating of glass (Kohn et al. 1992; Alloway et al. 1993) at 0.35 Ma. It also has been identified clearly within Wanganui Basin in non-marine

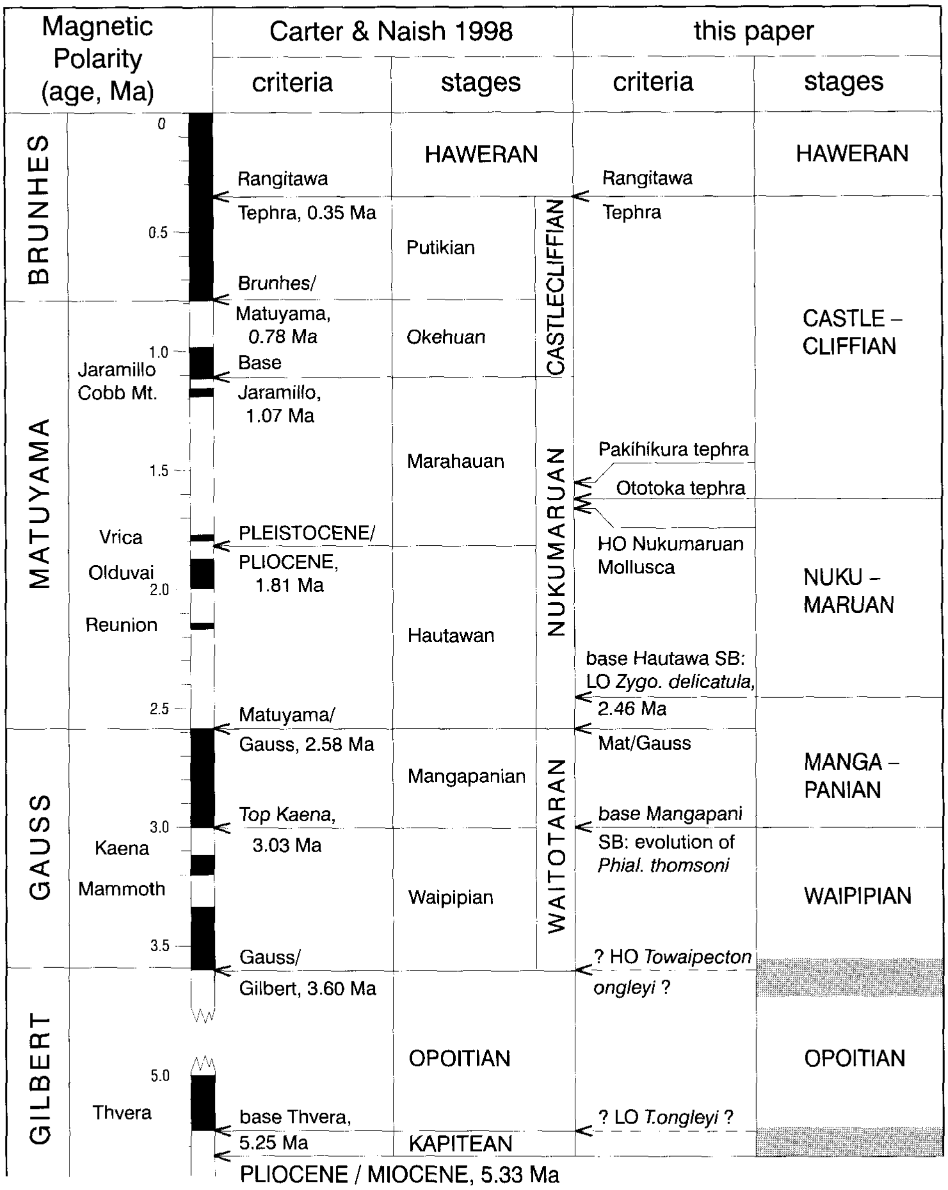

Fig. 3 Comparison of Wanganui Series chronostratigraphic scales and characterising criteria, suggested by Carter & Naish (1998) (central column) and in this paper (right column), with the standard magnetic polarity timescale (left column; from Carter & Naish 1998). Shaded areas indicate zones of uncertainty of stage boundary positions. Abbreviations: HO – highest occurrence; LO – lowest occurrence; SB – shellbed.

strata, and has been identified widely elsewhere in New Zealand in loess and other non-marine rocks. It occurs, also, in the core from DSDP Site 594, in the Bounty Trough, east of the central South Island, along with probable occurrences in several other cores from around New Zealand (Kohn et al. 1992). In Wanganui Basin and some offshore cores, Rangitawa Tephra is identified as lying within the deposits of glacial OIS 10, so that all marine and non-marine units of OIS 9 and younger confidently could be assigned to the Haweran Stage if this tephra is used to characterise the boundary. An SSP for the Haweran Stage therefore is recommended at the base of Rangitawa Tephra in Rangitawa Stream, Rangitikei valley.

At its type locality, Rangitawa Tephra crops out on the northern (south-facing) cliff of the small gorge of Rangitawa Stream at grid reference S23/196164 (all grid references are to sheets of New Zealand Map Series 260, 1: 50 000). The outcrop is in a short, straight, east–west section of Rangitawa Stream, c. 200 m north of the Kakariki-Halcombe Road and c. 2.5 km east of Kakariki Bridge (which crosses the Rangitikei River), on the east side of the Rangitikei valley, c. 8 km northeast of Bulls and 8 km southeast of Marton.

2. Castlecliffian SSP: The position identified by Fleming (1953, 1959), at the angular unconformity at the base of Butlers Shell Conglomerate in the Wanganui coastal section, is the least useful position for a stage boundary (Salvador 1994). Carter & Naish (1998) suggested that the boundary should be redefined at the base of Jaramillo Subchron (1.07 Ma) but, despite its closeness to a suitable visible proxy in the form of Potaka Tephra (1.05 Ma), this level is inappropriate. It would leave a succession of rocks containing undoubtedly Castlecliffian molluscs in the Rangitikei valley, in eastern Wanganui Basin, languishing within the Nukumaruan Stage. It therefore would remove all possibility of using biostratigraphic criteria to recognise this stage boundary in frontier situations. Research is under way (Beu, Naish & Pillans, "Definition of a new boundary stratotype for the Castlecliffian Stage", in prep.) to define a new SSP near the top of Pukekiwi Shell Sand (HO of the Nukumaruan molluscs *Patro*, *Spisula*, *Pteromyrtea*, *Paphies* *crassiformis* (Marshall & Murdoch), and *Eumarcia*), in the coastal section at Ototoka Beach, west of Wanganui. However, the thick, completely exposed section in the Rangitikei River, farther east in Wanganui Basin, demonstrates that c. 350 m of rock (seven sedimentary cycles), spanning the correlated position of the stage boundary, is dominated by non-marine to marginally marine lithologies. These form part of the 11 cycles (comprising OIS 32–54) in inland sections that fall within the angular unconformity at Castlecliff. This marked shallowing to near the shoreline characterises depositional environments in the late Nukumaruan to early Castlecliffian part of the column throughout Wanganui Basin. This means that few biostratigraphic criteria are available throughout Wanganui Basin to define this boundary, and it seems more appropriate to use one of the many tephras near this horizon as the stage boundary event. The best contender is perhaps the Pakihikura tephra, which is a particularly thick and widespread tephra recognised widely around New Zealand (Alloway et al. 1993), and which was adopted by Te Punga (1952) as the Nukumaruan/Castlecliffian Stage boundary marker in the Rangitikei River succession. The Pakihikura tephra has a newly determined numerical age of 1.57 ± 0.05 Ma (weighted mean average of five ITPFT determinations; B. V. Alloway, GNS, pers. comm. April 2000). However, this tephra does not crop out in the coastal section, and so probably again falls within the angular unconformity at the coast. Therefore, it would be more appropriate to define the Castlecliffian SSP at the base of the Ototoka tephra, newly identified within Upper Maxwell Formation in the coast section and at an equivalent position in the Rangitikei River section (B. J. Pillans, ANU, pers. comm.). The coastal and Rangitikei River sections then unequivocally can be correlated. This tephra lies a short stratigraphic interval above the highest Nukumaruan Mollusca in both the coastal and Rangitikei River sections, and so the HO of Nukumaruan Mollusca still could be used as a stage boundary proxy if the base of this tephra at Ototoka Beach was defined as the SSP. An SSP for the Castlecliffian Stage, therefore, is recommended at the base of the Ototoka tephra in the coastal section at Ototoka Beach, Wanganui.

The locality is at grid ref. R22/667473, high in the bluff immediately east of the mouth of Ototoka Stream, a short distance below the angular unconformity (where Castlecliffian Butlers Shell Conglomerate rests on Nukumaruan Maxwell Group) at the end of Ototoka Beach Road. This is a public but little-formed access road to Ototoka Beach, crossing farmland for 4 km southwest from the junction of Maxwell Station and Handley Roads (junction at grid ref. R22/696477), c. 6 km south of the township of Maxwell, on the main Wanganui–New Plymouth highway c. 12 km west of Wanganui. The outcrop is in the Ototoka Stream face of Ototoka Bluff (Fleming 1953, fig. 34), in the main coastal Nukumaru–Castlecliff section, c. 6 km west of the bridge over Kai-Iwi Stream, Kai-Iwi Beach, and c. 10 km west of the end of the road at Karaka Street, Castlecliff, Wanganui.

3. Nukumaruan SSP: The best locality and horizon for the definition of a basal Nukumaruan SSP characterised by biostratigraphic criteria still seems to be the base of Hautawa Shellbed at old Hautawa Road (extending to the west of West Road), north of Hunterville in the Rangitikei valley. The boundary then would be characterised by the lowest occurrence of *Zygochlamys delicatula* in Wanganui Basin. Although this criterion is highly facies dependent, recognition of this horizon within Wanganui Basin has proved easy during the many recent mapping and sequence stratigraphic studies of the basin. It also has been reasonably certainly identified outside the basin (in Wairarapa and Hawke's Bay; Hornibrook 1981; Scott et al. 1990) by correlation using the planktonic foraminifera *Globorotalia crassula* and dextral *G. crassiformis*. It is conceivable that early Nukumaruan rocks in North Canterbury could demonstrate that the LO of *Z. delicatula* in that region occurred at the same level as in Wanganui Basin (OIS 98; Naish et al. 1997, 1998; Carter & Naish 1999), and that the LO of *Z. delicatula* is a reliable biostratigraphic criterion. It certainly is greatly preferable to define the base Nukumaruan SSP at the base of Hautawa Shellbed at old Hautawa Road, and to use the LO of *Z. delicatula*, along with planktonic foraminifera, to characterise the boundary away from old Hautawa Road, than to use the position recommended by Carter & Naish (1998). They selected the Gauss/Matuyama magnetic polarity transition (2.58 Ma) as the Nukumaruan/Mangapanian boundary. However, this transition occurs at the base of Parihauhau Shellbed, which correlates with the base of OIS 104 (Carter & Naish 1998, fig. 2), significantly below the base of Hautawa Shellbed. This position for the stage boundary, therefore, would remove all possibility of using biostratigraphic criteria to recognise the stage boundary in frontier situations. An SSP for the Nukumaruan Stage, therefore, is recommended at the base of Hautawa Shellbed at old Hautawa Road, north of Hunterville in the Rangitikei valley.

Hautawa Road (now a disused, grassed platform on the hillside to the south of and above Hautawa Stream) extends east from Turakina Valley Road (joining it at Otiwhiti Station, grid ref. S22/235476) to West Road, Murimotu valley, north of Hunterville (joining West Road at the top of the hairpin bend 2 km west of Murimotu Road, at grid ref. T22/332483). The easiest access is by foot from the West Road end of Hautawa Road, which is c. 12 km north of the junction of Murimotu Road and Highway 1; the junction is 3 km northeast of Hunterville, Rangitikei valley. Hautawa Shellbed is exposed in cuts along the south side of Hautawa Road for at least 0.5–7.0 km west of the junction with West Road, and good outcrops were observed recently between grid ref. T22/327483 and 318483. An SSP for the Nukumaruan Stage would be most appropriately located in this area of Hautawa Road.

4. Mangapanian SSP: Carter & Naish (1998) chose the top of Kaena Subchron (3.03 Ma) as the stage boundary criterion for the base of the Mangapanian Stage. However, the best locality and horizon for a basal Mangapanian SSP still appears to be the one used by Fleming (1953) for the base of the stage, and described by Beu (1995, p. 22). This is the base of Mangapani Shellbed c. 2 km east of Waitotara Valley Road in the Mangapunipuni Stream valley, a tributary of Waitotara River valley, west of Wanganui. The basal *Phialopecten* shellbed of Mangapani Shellbed at this locality is the one place in New Zealand where an intermediate population is preserved recording a speciation event, when *P. marwicki* abruptly evolved into *P. thomsoni*. Large specimens (particularly right valves) clearly resemble

P. thomsoni more nearly than *P. marwicki*. As the *Phialopecten* lineage is the most useful biostratigraphic tool for the recognition of stages in shallow-water facies, such as limestone, throughout the Pliocene in New Zealand (Beu 1995), selection of an SSP at this position is crucial for maintaining the utility of the lineage in biostratigraphy. The top of Kaena Subchron is only slightly older than the base of 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. An SSP for the Mangapanian Stage, therefore, is recommended at the base of Mangapani Shellbed in Mangapunipuni Stream, Waitotara valley.

The most suitable location for the SSP of the base of the Mangapanian Stage is where Mangapani Shellbed is exposed best in a low bluff (at grid ref. R21/674614), on the south side of the main Mangapunipuni Stream valley immediately east of the junction with the first major side stream entering from the southeast. The locality is c. 2.2 km along the unformed "Waitotara Road" (on map sheet R21) east of Puao, a locality on Waitotara Valley Road c. 13 km north of Waitotara, a township on the main Wanganui–New Plymouth highway, c. 20 km west of Wanganui.

5. Waipipian and Opoitian SSPs: These SSPs both require further research before their positions are designated. Beu et al. (1987) and Beu (1995) suggested that, on the basis of *Phialopecten* biostratigraphy, the Waipipian/Opoitian boundary should be placed at the angular unconformity between Tahaenui Limestone (Waipipian) and Whakapunake Limestone (Opoitian) at the downstream mouth of Haupatanga Gorge, Mangapoike River, northern Hawke's Bay. However, this position at an angular unconformity is unacceptable. It is suggested on the accompanying diagram (Fig. 3), comparing the time-scales suggested by Carter & Naish (1998) and in this paper, that the LO and HO of the pectinid *Towaipecten ongleyi* might be used as biostratigraphic recognition criteria for base Opoitian and base Waipipian Stages, respectively. These allow easy recognition of the stage boundaries in shallow-water facies in the eastern North Island (Beu 1995). However, they are of no use in the widespread outer shelf to bathyal mudstone in eastern North Island, and *T. ongleyi* has not been reported from Wanganui Basin. Other recognition criteria would be more desirable than the LO and HO of *T. ongleyi*. It is now clear that continuous sections through rocks of at least the Tongaporutuan–Waipipian Stages (late Miocene – middle Pliocene) are well exposed in several rivers in Wanganui Basin (Waitotara, Rangitikei and, in particular, Wanganui Rivers; P. J. J. Kamp, University of Waikato, pers. comm.). SSPs of the Waipipian and Opoitian Stages would be best defined in one of these sections. Much of the succession is cyclic, so that molluscan faunas in basal transgressive shellbeds in each cycle alternate with useful foraminiferal faunas, including some planktic foraminifera, in the intervening high-stand mudstone units. The Wanganui River section, in particular, offers the hope of an integrated biostratigraphy of molluscs and foraminifera. This would greatly help biostratigraphy in geographically distant localities where facies are more limited, and biostratigraphy must depend only on one group or another. Also, magnetic polarity stratigraphy of the Wanganui and Rangitikei River sections already has been determined (P. J. J. Kamp, University of Waikato, pers. comm.) and can be integrated with the biostratigraphy. SSPs of the Waipipian and Opoitian Stages are recommended to be located in the Wanganui River section, but much further research is required to determine the most appropriate positions for these two SSPs.

The section is exposed virtually continuously from the upstream end of Wanganui City, and particularly along the Wanganui River Road on the east bank of Wanganui River upstream from Upokongaro (joining the Parapara Road 2 km north of Upokongaro, at gird ref. S22/621487), extending for c. 50 km north to Pipiriki (at grid ref. R21/857898). Much of this section is exposed moderately well along the road, but this area is more accessible by boat, and the 30+ km of further section upstream from Pipiriki is only accessible by boat. However, the entire section is easily reached by jet-boat, and the area upstream from Pipiriki exposes a progressively older section of cyclothemic Miocene rocks underlying the thick Pliocene section, as yet little studied but clearly important on a world scale for Neogene stratigraphy.

CONCLUSIONS

1. Definitions of New Zealand Pliocene–Pleistocene local stages by Carter & Naish (1998) ignore the main purpose of a stage classification, objectively to order local strata on the basis of local criteria. Their definitions concentrate on international correlation, the secondary aim of a stage classification, and need reconsideration. The most easily recognised chronostratigraphic subdivision of New Zealand rocks, using integrated biostratigraphic and physical stratigraphic methods, should be determined objectively before correlation with the international time-scale is attempted.
2. Fleming (1953) proposed two alternating sets of "cool" and "warm" substages for the Castlecliffian and Nukumaruan Stages, because he thought they should be recognisable for the New Zealand succession to match the four glaciations then recognised in Europe. Carter & Naish (1998) resurrected the substages of the Nukumaruan and Castlecliffian Stages, but these are unhelpful. It would be more useful to subdivide the regional stages at the level of OISs.
3. Biostratigraphically characterised stages are needed for the Pliocene–Pleistocene as much as for all other time periods in New Zealand, for the recognition of an independent New Zealand time-scale characterised by New Zealand fossils. They always will be much more rapid and cost effective than physical methods for subdividing rocks in frontier applications. Physical stratigraphic horizons (particularly visible ones, such as tephras) usefully can be integrated with the biostratigraphic criteria to refine the stage boundary definitions, especially for periods when few biostratigraphic events are available.
4. Stages recommended for recognition, and suggested positions of their SSPs, are as follows:
   a. Haweran Stage: SSP at base of Rangitawa Tephra (0.35 Ma), Rangitawa Stream, Rangitikei valley.

b. Castlecliffian Stage: SSP at base of the Ototoka tephra (within Upper Maxwell Formation), Ototoka Beach, Wanganui. This lies only slightly higher in the section than the top of Pukekiwi Shell Sand (HO of Nukumaruan molluscs), and only slightly lower than the Pakihikura tephra (1.57 Ma).

c. Nukumaruan Stage: SSP at base of Hautawa Shellbed (OIS 98, c. 2.46 Ma), old Hautawa Road, off West Road, Rangitikei valley (LO of *Zygochlamys delicatula*). This position is not far above the Gauss-Matuyama magnetic transition (2.58 Ma).

d. Mangapanian Stage: SSP at base of Mangapani Shellbed, Mangapunipuni Stream, Waitotara valley (evolution from *Phialopecten marwicki* to *P. thomsoni*, that is, LO of *P. thomsoni*). This lies only a short stratigraphic distance above the top of Kaena Subchron (3.03 Ma).

e. Waipipian and Opoitian Stages: SSPs to be defined after further research, preferably in the Wanganui River section.

ACKNOWLEDGMENTS

A visit to the Wanganui River section with Peter Kamp (University of Waikato) opened my eyes to the prospects for stage definitions in this amazing section. He also provided information on the Cape Kidnappers section. Brad Pillans (ANU) and Tim Naish (IGNS) provided helpful advice on tephras and lithostratigraphy, and Brent Alloway (IGNS) provided a new date for the Pakihikura tephra. I am most grateful for helpful suggestions to improve the manuscript by Roger Cooper, James Crampton and Chris Hollis (IGNS), Brad Pillans, and the referees, Bill Berggren (Woods Hole Oceanographic Institute) and Peter Kamp. Phillip Carthew (IGNS) drafted the diagrams. Institute of Geological & Nuclear Sciences contribution number 1909.

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