Revised calibration of the New Zealand Geological Timescale: NZGT2015/1

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ABSTRACT

The criteria used to establish the age ranges of New Zealand stages (and some substages) for late Paleozoic to Cenozoic time are reviewed and the ages re-calibrated to the 2014 International Geological Timescale, taking into account recent stratigraphic data from New Zealand studies. This updated New Zealand timescale is referred to as NZGT2015/1. The age calibration is compared to the comprehensive review of 2004, a Cretaceous-Cenozoic review in 2010, and an interim calibration in 2012. In the Cretaceous and Cenozoic, boundary age changes since 2010 are most significant in stages of the Raukumara to Arnold Series (Cenomanian to late Eocene), but several stages of the Landon to Wanganui Series (Oligocene to Pliocene) are also affected. Calibration of the Permian to Jurassic New Zealand timescale comprises the first such general review since 2004: boundary ages of nearly all stages are revised, as well as definitions of the upper and middle Ohauan and upper Heterian substages (Upper Jurassic). Australasian stages are used in New Zealand for the Cambrian and Ordovician periods, but international units for the Silurian to Carboniferous: for these we report age calibration based on 2012 and 2014 international compilations.

KEYWORDS

geological timescale, chronostratigraphy, biostratigraphy, magnetostratigraphy, Cenozoic, Mesozoic, Paleozoic, Neogene, Paleogene, Cretaceous, Jurassic, Triassic, Permian, Pleistocene, Pliocene, Miocene, Oligocene, Eocene, Paleocene, New Zealand, stages, substages, series

1.0 INTRODUCTION

Age estimates of New Zealand Cretaceous and Cenozoic stage boundaries made in the major 2004 revision of the New Zealand Geological Timescale (Cooper 2004) were based on age calibrations of the Geomagnetic Polarity Timescale and global stages and bioevents provided for the Cretaceous by Ogg et al. (2004)[1], and for the Cenozoic by Cande & Kent (1995) and Berggren et al. (1995a). A variety of independent data such as New Zealand isotopic dates was also used. For preceding Phanerozoic periods, calibration was based mainly on faunal and floral correlations with global stages, using calibrations of the latter which best fitted available New Zealand isotopic dates and apparent stage durations, as described in Cooper (2004). This calibration was also issued in 2004 and 2006 in the form of wall charts and in 2004 and 2005 as pocket cards.

Calibration of global stages in the internationally used Global Geochronological Scale is an on-going process, and a new age calibration "GTS2004" was published by Gradstein et al. (2004) in the same year as the New Zealand work. GTS2004 incorporated age calibrations for some global events that differ from those used in Cooper (2004). A re-evaluation of the ages of New Zealand Cretaceous and Cenozoic stage boundaries was therefore undertaken by Hollis et al. (2010) to calibrate them to GTS2004, incorporating the modifications introduced by Ogg et al. (2008) and also some more recent New Zealand work. This calibration "NZGTS 2010/1" was also issued (with slight differences in calibration for some stages) as a pocket card, and online wall chart and table. On the pocket card, ages of Permian to Jurassic New Zealand stage boundaries were not amended from those of Cooper (2004), but those of global stages were revised to those of Ogg et al. (2008), resulting in a mismatch. Ages of Australasian and global Cambrian to Carboniferous stages also followed Ogg et al. (2008).

A further major calibration of the Global Geochronological Scale was published by Gradstein et al. in mid-2012, and based on this an interim new calibration of the New Zealand Geological Timescale, v. 2012/1 (NZGT2012) was issued as a pocket card later that year (Raine et al. 2012). This calibration, which encompassed a re-evaluation of the complete New Zealand Phanerozoic stage sequence, was later placed on the GNS Science website as a downloadable chart and table.

The GNS Science Report which was intended to accompany NZGT2012 remained in draft form, and was overtaken in 2013 by a new calibration of the Global Geochronological Scale provided by the various sub-commissions of the International Commission on Stratigraphy (Cohen et al. 2013). This was very slightly updated in 2014 (Cohen et al. 2014). In the Phanerozoic Era for the most part this calibration matches that of Gradstein et al. (2012), but there are significant differences in calibration of stage boundaries in the Permian, Triassic, and Lower Cretaceous, and minor differences in the Pleistocene (Table 1, at end of report). Revised correlation of some New Zealand stages and other minor corrections also necessitated a revision of the 2012 New Zealand calibration. This is described in the current report, with a new timescale calibration designated "NZGT2015/1".

[1] The ages used in Cooper (2004) were in fact pre-publication ages supplied by Prof. Ogg that changed very slightly prior to final publication of Ogg et al. (2004). Consequently, ages assigned to the bases of the Turonian, Coniacian and Santonian stages vary by up to 0.2 Ma between Cooper (2004) and Ogg et al. (2004).

For each stage and substage, the current definition is summarised and is followed by comments on the revised age calibration. In most cases, a more comprehensive review of correlation criteria and precision of calibration is given by Cooper (2004). The 2015 New Zealand Geological Timescale is shown in Figure 2 to Figure 11; New Zealand map codes and colours are also indicated. Table 2 (at end of report) compares the 2015 calibration with the calibrations made in 2004, 2010, and 2012.

Concepts of unit stratotype and boundary stratotype follow Cooper (2004, p.4); Table 2 lists progress with definition of a stratotype section and point (SSP) for each New Zealand stage. Lowest Occurrence (LO) and Highest Occurrence (HO) refer to locally (New Zealand) recognised events (following Cooper 2004); First Appearance Datum (FAD) and Last Appearance Datum (LAD) refer to globally defined events (following Berggren et al. 1995a). For the geomagnetic polarity timescale, we make no terminological distinction between "Chron", "Subchron" and "Infrachron". A decimal fraction following the chron designation refers to the location of the event from the *base* of the chron, being proportional to the length of the chron, e.g. C4An.43 signifies a position above base of 43% of the length of the chron. This practice follows that in Gradstein et al. (2012).

The dates assigned to many of the Cenozoic biostratigraphic events are based on their occurrences in drill holes drilled by the Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP). Because ages of these events generally vary with watermass, New Zealand region drill sites have been preferred where suitable data is available - sites referred to in the text are shown in Figure 1.

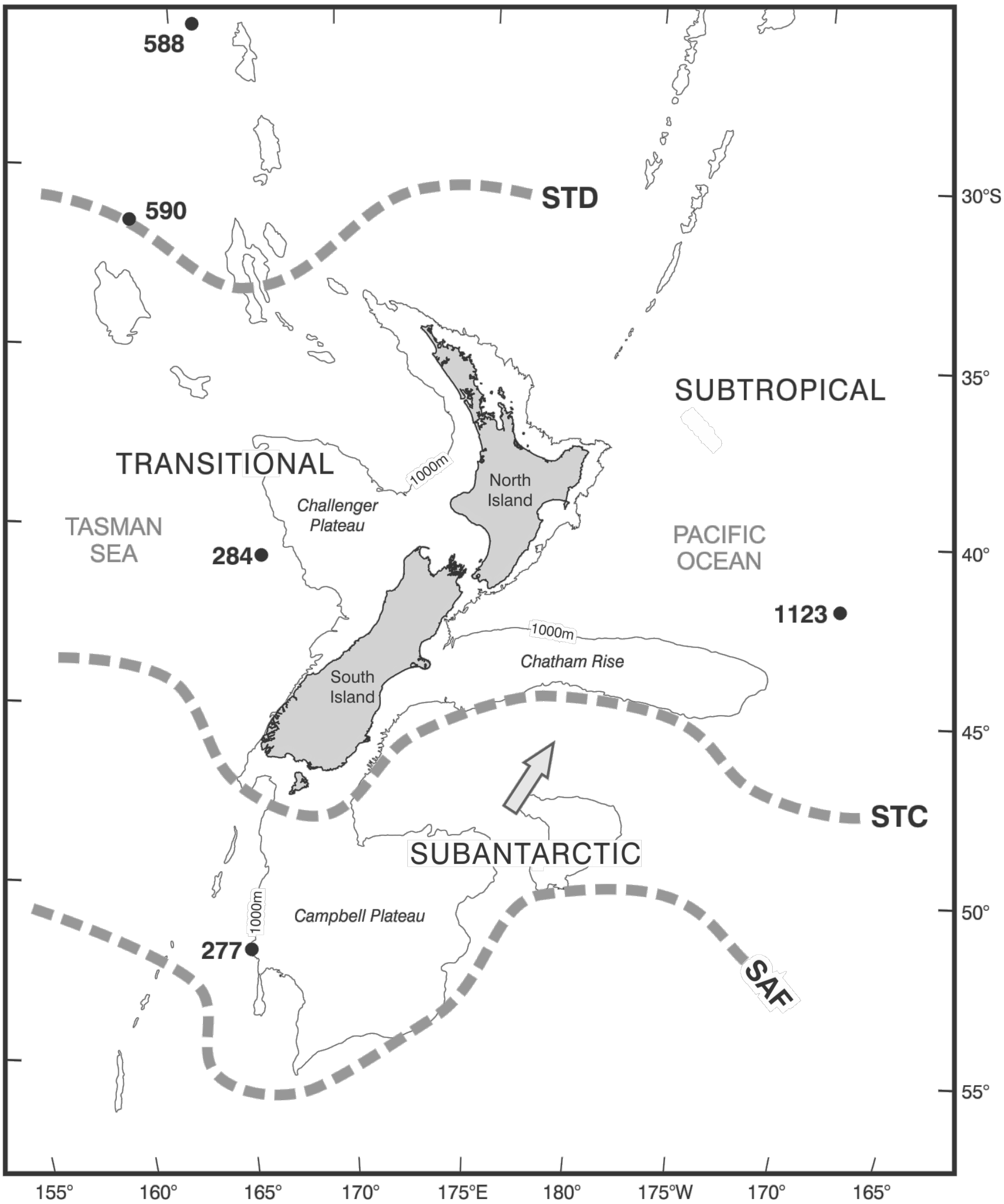

Figure 1 Present-day oceanographic setting for New Zealand and location of DSDP and ODP drill sites mentioned in the text (adapted from Crundwell & Nelson 2007). Abbreviations: STD - Tasman Front, STC – Subtropical Front, SAF – Subantarctic Front.

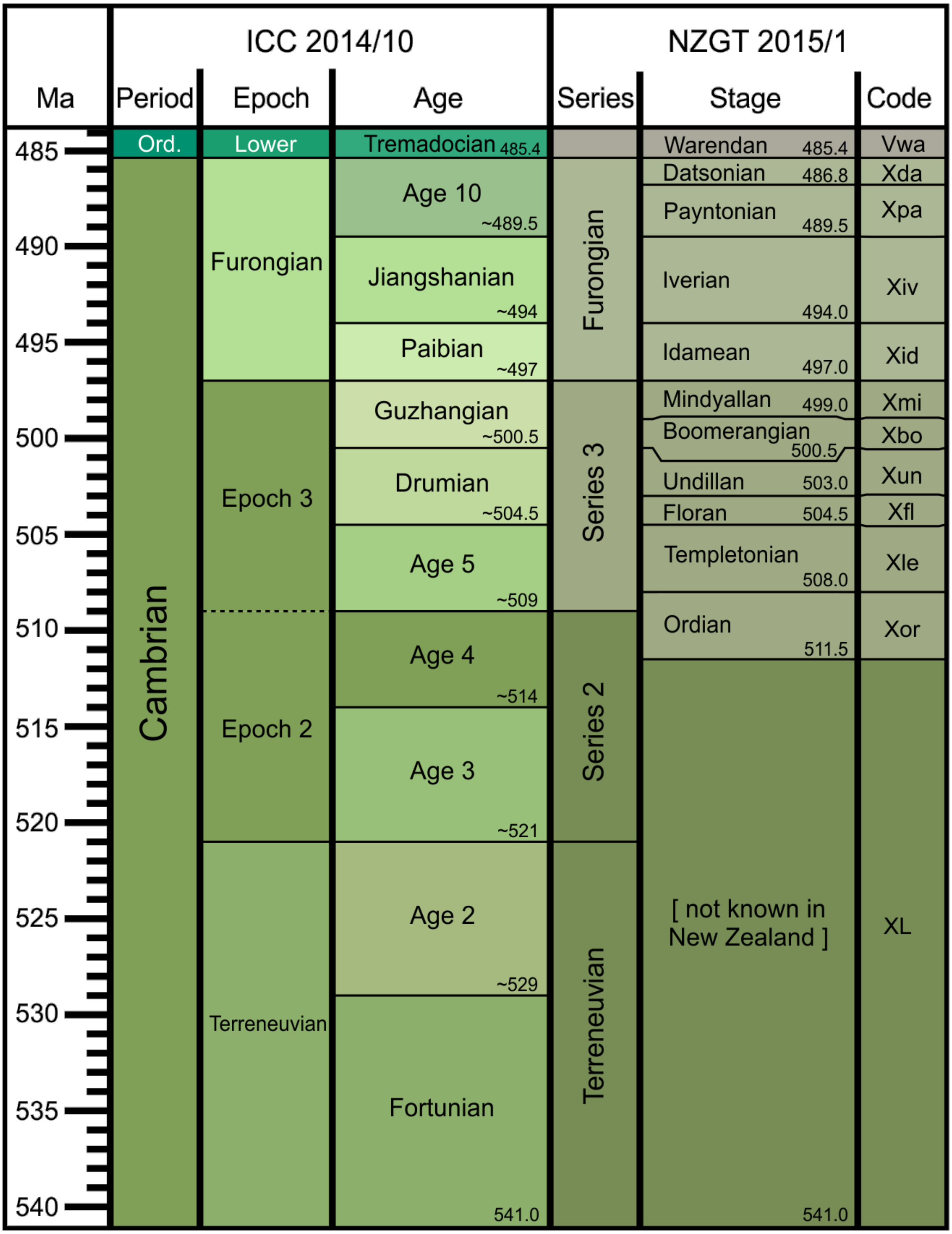

Figure 2 Cambrian Timescale. Based on the 2014 International Chronostratigraphic Chart (ICC 2010/10, Cohen et al. 2014). Australasian stages are correlated as in Gradstein et al. (2012).

2.0 CAMBRIAN

In the New Zealand Cambrian, trilobites are the most abundant fossil group and also most important for biostratigraphy. Strong faunal provincialism characterised the Cambrian. The New Zealand faunas are most closely related to those of Australia, and Australian stages are therefore used as a chronostratigraphic framework for New Zealand strata (Cooper 2004). The age calibration of international and Australasian divisions, following Gradstein et al. (2012) and Cohen et al. (2014), is shown in Figure 2.

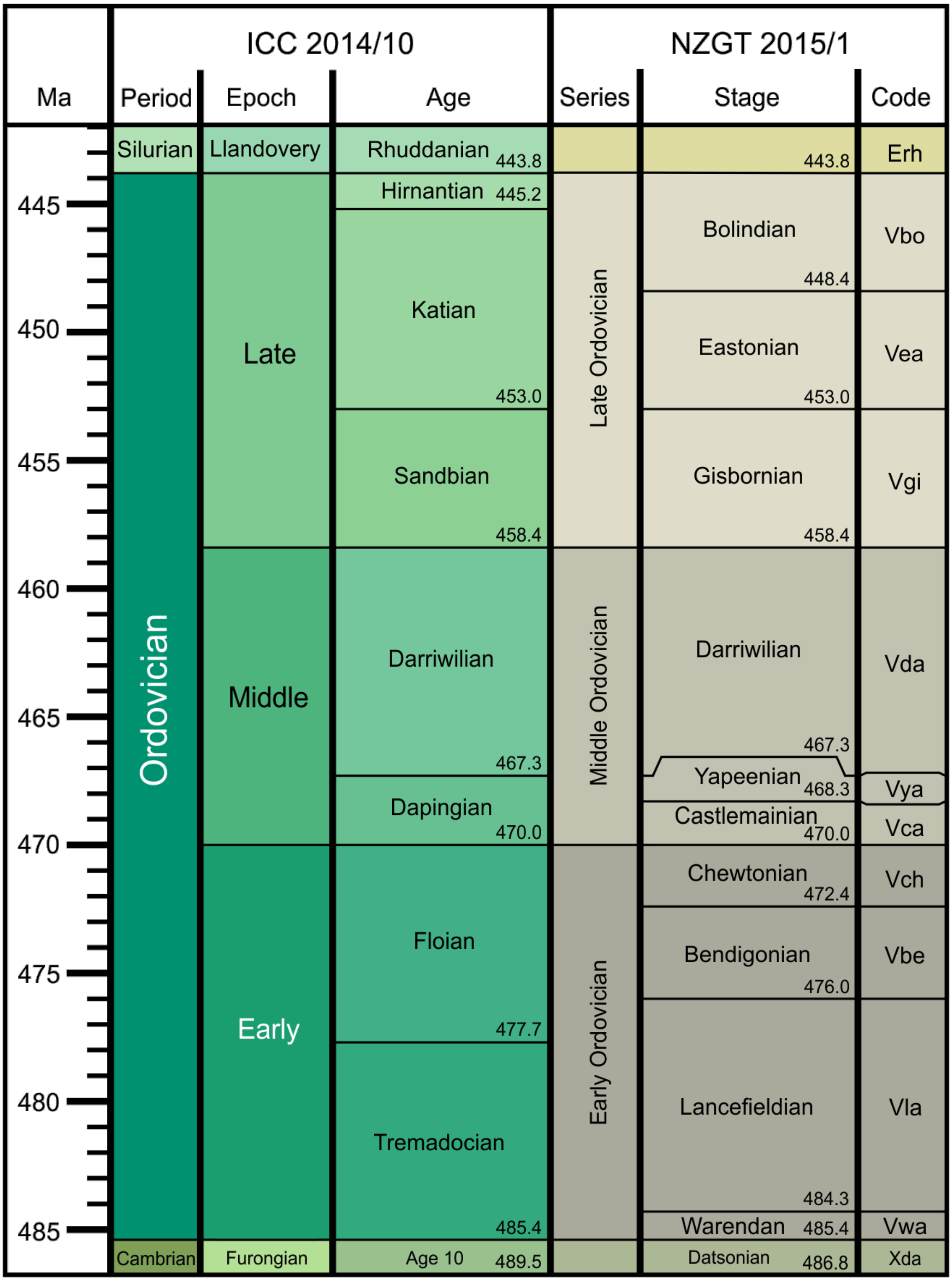

Figure 3 Ordovican Timescale. Based on the 2014 International Chronostratigraphic Chart (ICC 2010/10, Cohen et al. 2014). Australasian stages are correlated as in Gradstein et al. (2012).

3.0 ORDOVICIAN

As for the Cambrian, strong faunal provincialism obtained throughout most of the Ordovician, and although an international standard scheme of chronostratigraphic subdivision has been constructed in recent years, regional chronostratigraphic schemes continue to have significant utility. In Australia and New Zealand graptolites are the most important fossil group for subdivision and correlation of Ordovician rocks, and the regions share a common graptolite succession. This has been used as the basis for a common set of Australasian stages and zones (Thomas 1960; Vandenberg & Cooper 1992, Cooper 2004). The age calibration of international and Australasian divisions, following Gradstein et al. (2012) and Cohen et al. (2014), is shown in Figure 3.

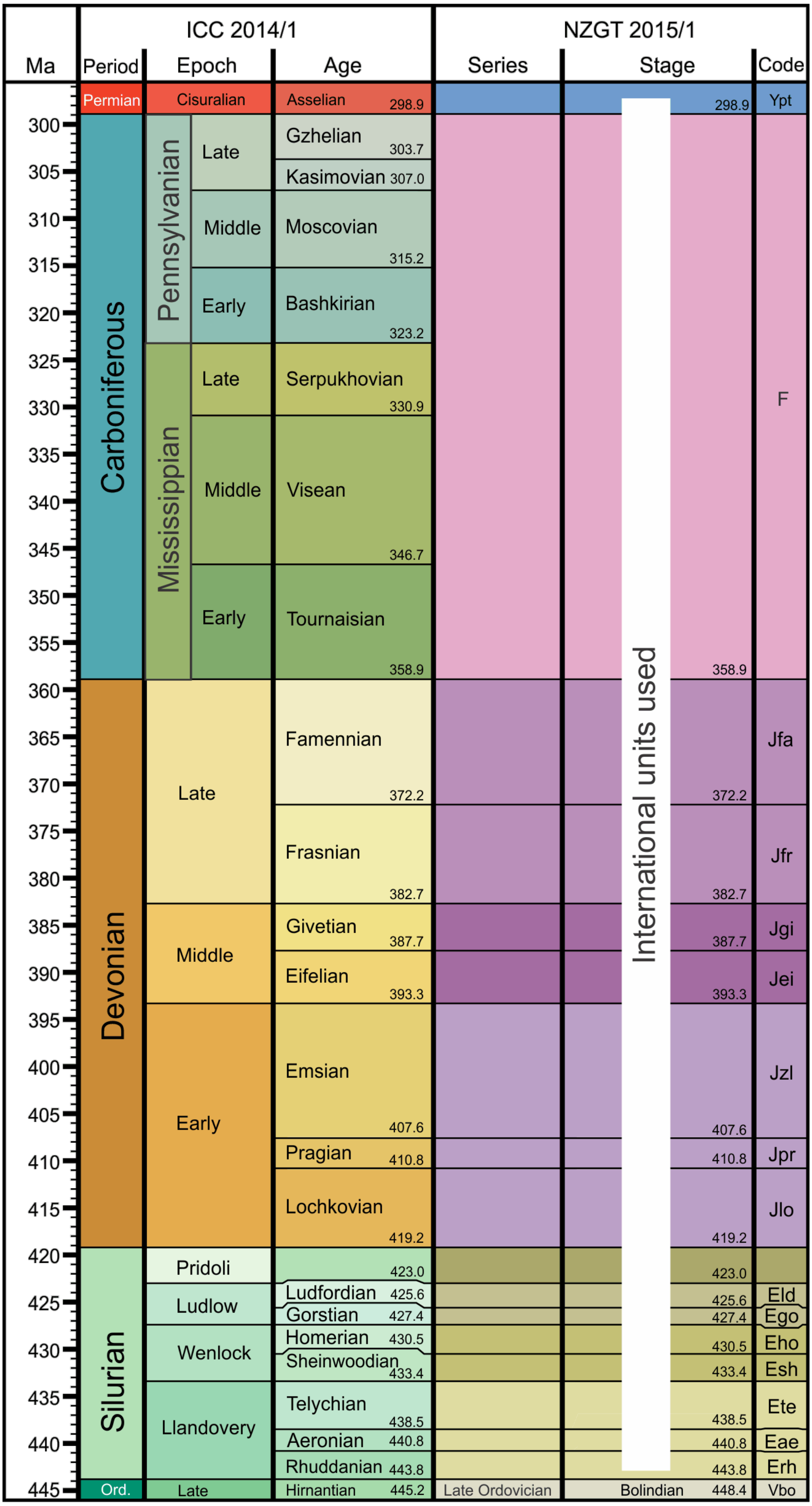

Figure 4 Silurian to Carboniferous Timescale. Based on the 2014 International Chronostratigraphic Chart (ICC 2010/10, Cohen et al. 2014).

4.0 SILURIAN TO CARBONIFEROUS

Rocks of Silurian to Carboniferous age are poorly represented in New Zealand (Cooper 2004), and no local chronostratigraphic units are currently recognised. International divisions have been used for correlation and subdivision of those strata that do occur. The age calibration of international divisions by Cohen et al. (2014) does not differ from that in Gradstein et al. (2012), and is shown in Figure 4.

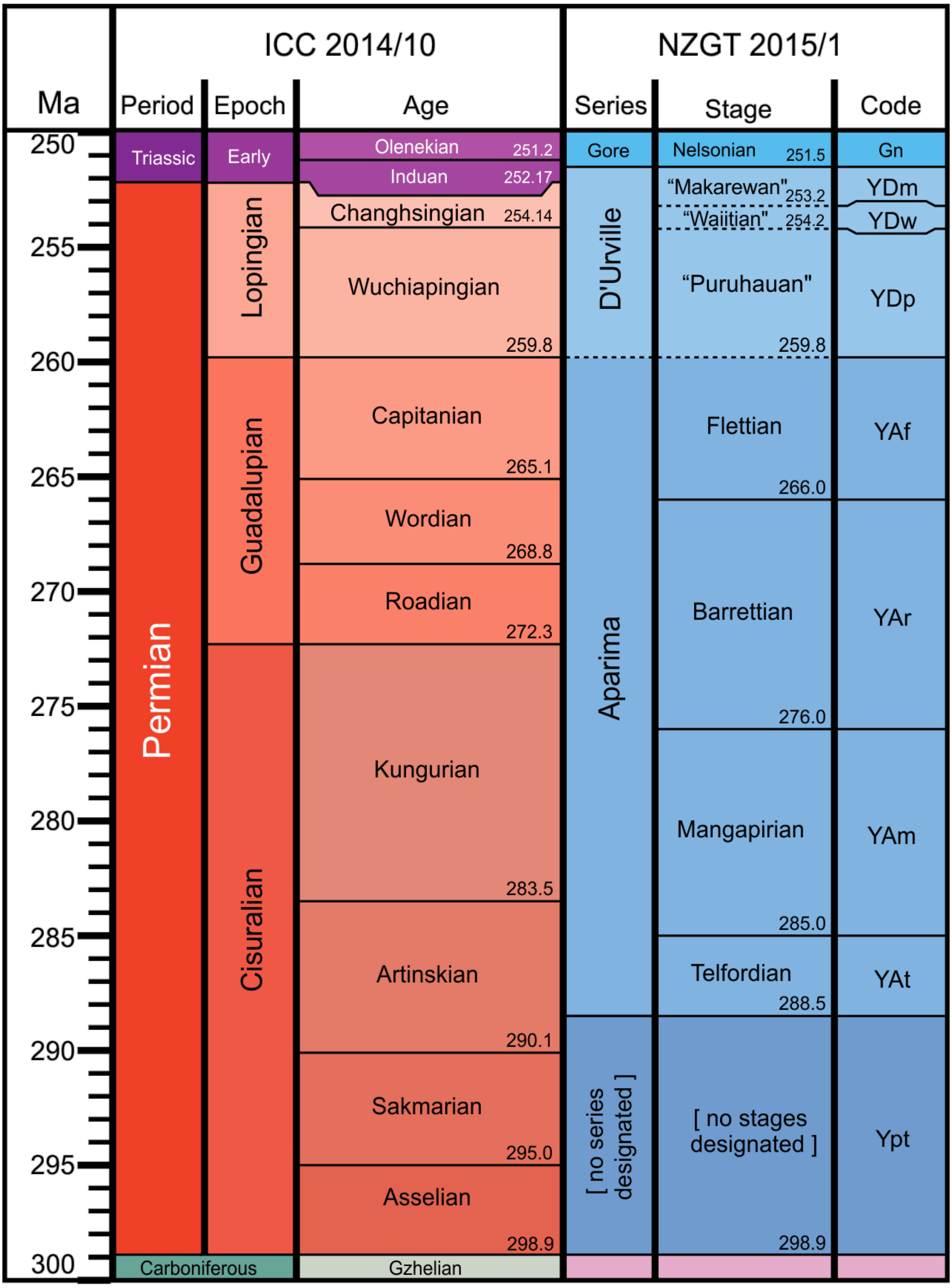

Figure 5 Permian Timescale. The 2015 calibration of D'Urville and Aparima Series stages with the Global Geochronological Scale for the Permian Period, as published in the 2014 International Chronostratigraphic Chart (ICC 2010/10, Cohen et al. 2014). New Zealand series and stages for the Carboniferous and pre-Telfordian Permian have not been defined.

5.0 PERMIAN

The ages of Permian stage boundaries given by Cohen et al. (2014) are identical with those provided by the Subcommission on Permian Stratigraphy (Shen et al. 2013), and differ from those of Gradstein et al. (2012) slightly for the Changhsingian (254.14 Ma versus 254.2 Ma in Gradstein et al.) and Sakmarian (295.0 Ma versus 295.5 Ma) but more significantly for the Kungurian (283.5 Ma versus 279.3 Ma). Correlation of the New Zealand stages remains very approximate and therefore we have not revised the age calibrations from Raine et al. (2012). The NZGT 2015/1 calibration is illustrated in Figure 5.

5.1 BASE OF PERMIAN

- A pre-Telfordian fauna of late Sakmarian age is known from New Zealand (Cooper 2004), but no local stages have been defined.
- Pre-Telfordian Permian time is therefore represented in New Zealand by an 'unassigned' time interval (see Cooper 2004) including the entire Asselian and Sakmarian Stages, and the lowermost part of the Artinskian Stage.
- The base of the Asselian Stage and Permian System is assigned an age of **298.9 Ma** by Cohen et al. (2014; 299.0 Ma in Cooper 2004).

5.2 BASE TELFORDIAN STAGE AND APARIMA SERIES

- Provisionally taken by Cooper (2004) as the LO of the brachiopod *Plekonella campbelli*. No SSP has been defined, but the Takitimu Group section in the Wairaki River valley, Southland was indicated as a "reference section" by Cooper (2004).
- Telfordian faunas are correlated with the lower Artinskian Stage (Cooper 2004).
- Based on the calibrated ages of the boundaries of the Artinskian Stage in Cohen et al. (2014), we assign the base of the Telfordian Stage an arbitrary interpolated age of **288.5 Ma** (283.0 Ma in Cooper 2004).

5.3 BASE MANGAPIRIAN STAGE

- LO of the brachiopod *Attenuatella altilis*. No SSP has been defined, but a Maclean Peaks Formation section in the Wairaki River valley, Southland, was indicated as "reference section" by Cooper (2004).
- Mangapirian faunas are correlated with the upper Artinskian and lower Kungurian Stages (Cooper 2004).
- Based on calibrated ages of the boundaries of the Artinskian Stage, 290.1 - 283.5 Ma in Cohen et al. (2014), we assign the base of the Mangapirian Stage an arbitrary interpolated age of **285.0 Ma** (280.0 Ma in Cooper 2004).

5.4 BASE BARRETTIAN STAGE

- LO of the brachiopod *Spiriferella supplanta*. No SSP has been defined, but a Mangarewa Formation section in a tributary of Letham Burn, Wairaki Hills, Southland was indicated as "reference section" by Cooper (2004).

- Barrettian faunas are correlated with the upper Kungurian to upper Wordian Stages (Cooper 2004).
- Based on calibrated ages of the boundaries of the Kungurian Stage, 283.5 - 272.3 Ma in Cohen et al. (2014), we assign the base of the Barrettian Stage an age of 276.0 Ma (273.0 Ma in Cooper 2004).

5.5 BASE FLETTIAN STAGE

- Base defined by LO of the brachiopod *Echinalosia ovalis*. No SSP has been defined, but a Mangarewa Formation section in a tributary of Letham Burn, Wairaki Hills, Southland was indicated as "reference section" by Cooper (2004).
- The Flettian fauna is correlated with the upper Wordian and Capitanian Stages (Waterhouse 1998, Cooper 2004).
- Based on calibrated ages of the boundaries of the Wordian Stage, 268.8 - 265.1 Ma in Cohen et al. (2014), we assign the base of the Flettian Stage an age of **266.0 Ma** (266.5 Ma in Cooper 2004).

5.6 "PURUHAUAN STAGE" AND D'URVILLE SERIES

- Originally defined (Waterhouse 1967) on the basis of a distinctive fauna within poorly exposed, structurally complex strata near Clinton, south Otago, the Puruhauan is currently regarded as an informal biostratigraphic unit. Definition of a lower boundary to the "stage" is inappropriate because of inadequate knowledge of stratigraphy in the type area, including lack of demonstrable relationship to underlying or overlying stages (Cooper 2004).
- The Puruhauan fauna is correlated with the Wuchiapingian Stage (Cooper 2004).
- Equivalent to the calibrated age for the lower boundary of the Wuchiapingian Stage in Cohen et al. (2014), we assign the base of the Puruhauan Stage an arbitrary age of **259.8 Ma** (260.2 Ma in Cooper 2004).

5.7 "WAIITIAN STAGE"

- Originally defined (Waterhouse 1967) on the basis of a distinctive fauna within the Maitai Group at Wairoa Gorge, Nelson, the Waiitian is currently regarded as an informal biostratigraphic unit. The Wairoa fauna is now believed to occur in an allochthonous block within younger strata (Cooper 2004). Definition of a lower boundary to the "stage" is therefore inappropriate.
- The Waiitian fauna is correlated with the lower Changhsingian Stage (Cooper 2004).
- Based on the calibrated age for the lower boundary of the Changhsingian Stage in Cohen et al. (2014), we assign the base of the Waiitian Stage a rounded arbitrary age of **254.2 Ma** (253.5 Ma in Cooper 2004).

5.8 "MAKAREWAN STAGE"

- Originally defined (Waterhouse 1967) on the basis of a distinctive fauna within the Wairaki Formation, Wairaki Hills, Southland, the Makarewan is currently regarded as an informal biostratigraphic unit contained within an allochthonous sequence (Cooper 2004).

- The age and definition of the boundaries of the Makarewan are uncertain, but the brachiopod fauna is younger than that of the Waiitian (which is correlated with the lower Changhsingian Stage), and probably encompasses the upper Changhsingian Stage and the Permian-Triassic boundary (Cooper 2004), extending up to the base of the Nelsonian Stage.
- Using the calibrated ages of 254.14 - 252.17 Ma for the boundaries of the Changhsingian Stage in Cohen et al. (2014), we assign the base of the Makarewan Stage an arbitrary mid-Changhsingian age of **253.2 Ma** (252.25 Ma in Cooper 2004).

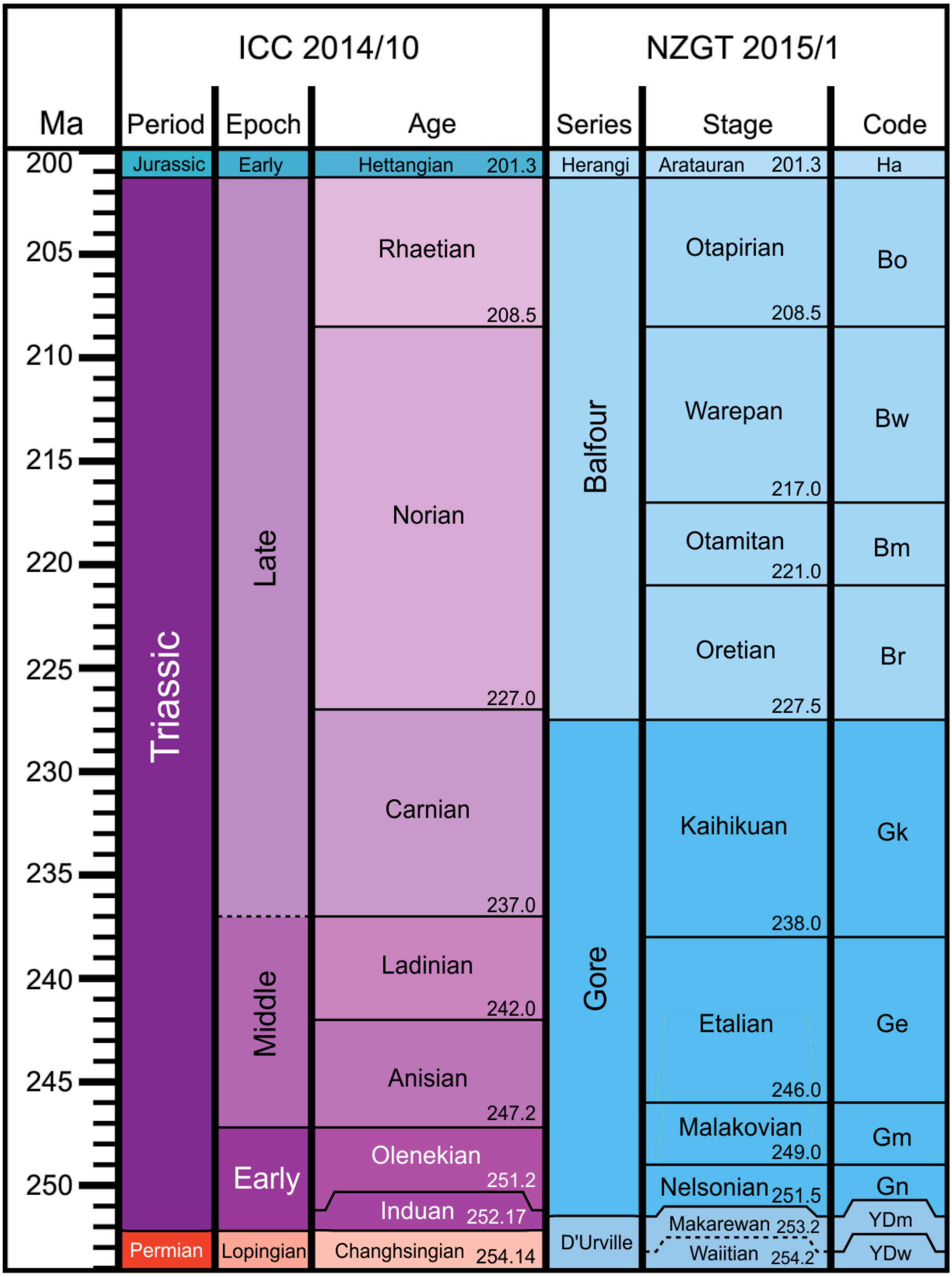

Figure 6 Triassic Timescale. The 2015 calibration of Balfour and Gore Series stages with the Global Geochronological Scale for the Triassic Period, as published in the 2014 International Chronostratigraphic Chart (ICC 2010/10, Cohen et al. 2014).

6.0 TRIASSIC

There are currently widely divergent opinions about calibration of the international Triassic stages, for example the Carnian/Norian boundary is placed by Lucas et al. (2012) at 220 Ma but by Gradstein et al. (2012) at 228.4 Ma and by Cohen et al. (2014) approximately at 227 Ma. There is also considerable uncertainty about the calibration of the Norian/Rhaetian boundary. See for instance Wotzlaw et al. (2014) who have suggested that the Rhaetian is only 4.1 Ma in duration with its base assigned to 205.5 Ma, based on radiometric dating from the Pucara Basin in Peru. Here we adopt the Cohen et al. (2014) calibrations but have also made judicious use of the intra-stage correlations provided by Gradstein et al. (2012). The NZGT 2015/1 calibration is illustrated in Figure 6.

6.1 BASE NELSONIAN STAGE AND GORE SERIES

- LO of the ammonoid *Durvilleoceras woodmani* in the Greville Formation section on the western coast of D'Urville Island (Cooper 2004).
- *D. woodmanii* and associated macrofauna in the boundary stratotype indicate that the base of the stage lies within the Induan Stage. The Permian-Triassic boundary is presumed to lie within the underlying (informal) "Makarewan Stage" (Cooper 2004).
- The base of the Induan Stage and Triassic System is calibrated at 252.17 Ma in Cohen et al. (2014; 252.20 Ma in Gradstein et al. 2012), but at 251.9 Ma in more recent work by Burgess et al. (2014). The base of the succeeding Olenekian Stage and hence upper boundary of the Induan is calibrated at 251.2 Ma by Cohen et al. (2014) but at 250.0 Ma in Gradstein et al. (2012), based on a different interpretation of isotopic dates. Here, the base of the Nelsonian Stage is arbitrarily assigned a "mid"-Induan age of **251.5 Ma** (250.4 Ma Cooper 2004, 251 Ma in Raine et al. 2012).

6.2 BASE MALAKOVIAN STAGE

- Begg (1981) and Campbell (1994) proposed that the base of the stage be defined at the LO of the ammonoid *Owenites* in the North Range Group section at Coal Creek, near Ohai, Southland, but because *Owenites* is so far known from only two localities in New Zealand this was not accepted by Cooper (2004).
- The Malakovian Stage apparently underlies the Etalian Stage stratotype and on the basis of its limited but distinctive ammonoid fauna was correlated with Tethyan and Boreal ammonoid zones (Kummel 1959, *Meekoceras gracilitatis* Zone; Begg 1981 and Begg et al. 1983, *Romunderi* and *Tardus* Zones) now placed in the lower Olenekian Stage (upper Smithian substage).
- Cohen et al. (2014) calibrate the boundaries of the Olenekian at 251.2 - 247.2 Ma, but Gradstein et al. (2012) give 250.0 - 247.1 Ma for the Olenekian and 250.0 - 248.5 for the Smithian. We correlate the base of the Malakovian Stage with the mid-Smithian and assign an arbitrary age of **249.0 Ma** (245.5 Ma in Cooper 2004, 246.5 Ma in Raine et al. 2012).

6.3 BASE ETALIAN STAGE

- LO of the gastropod *Mellarium* in the North Range Group section, Letham Burn, Wairaki Hills, Southland (Cooper 2004).

- The base of the Etalian Stage is correlated within the lower Anisian on the basis of ammonoids and the first appearance of the bivalve genus *Daonella* (Begg 1981, J.D. Campbell 1985, H.J. Campbell 1994, Cooper 2004).
- The base of the Anisian is calibrated by Cohen et al. (2014) at 247.2 Ma and by Gradstein et al. (2012) at 247.1 Ma. The base of the Etalian Stage is arbitrarily assigned an age of **246.0 Ma** (244.5 Ma in Cooper 2004, 245.5 Ma in Raine et al. 2012).

6.4 Base Kaihikuan Stage

- LO of the brachiopod *Alipunctifera kaihikuana* in the Taringatura Group section, Kaihiku Stream, Southland (Cooper 2004).
- The base of the Kaihikuan Stage is correlated with the *Sutherlandi* Zone (J.D. Campbell 1985, H.J. Campbell 1994), hence within the uppermost Ladinian Stage.
- Mundil et al. (2010) report a provisional CA-TIMS Pb-U zircon age of 237 Ma for a tuff within upper Etalian strata previously dated by Retallack et al. (1993) at 242.8 ± 0.6 Ma using $^{40}Ar/^{39}Ar$ measurements on biotite. However Cohen et al. (2014) assign an age of 237.0 Ma to the Ladinian/Carnian boundary (as did Gradstein 2012). Pending confirmation of the Mundil et al. (2010) upper Etalian tuff age, we rely on calibration of Boreal ammonoid zones by Gradstein et al. (2012) and place the base of the Kaihikuan at the base of the *Sutherlandi* Zone, **238.0 Ma** (238.5 Ma in Cooper 2004).

6.5 Base Oretian Stage and Balfour Series

- LO of the bivalve genus *Halobia* in the Taringatura Group section, Oreti River between Caroline and Dipton, Southland (Cooper 2004).
- The stratigraphically lowest *Halobia* species recorded in the Oreti River and other New Zealand sections is *Halobia (Halobia) austriaca* (Campbell 1994). Globally, *H. austriaca* is restricted to the uppermost Carnian-lowest Norian (*Macrolobatus* and *Kerri* Zones - Gruber 1976, Campbell 1994). A bioevent for the base-Norian global SSP is not yet defined, and may yet affect correlation of the FAD of *H. austriaca*, but provisionally we correlate the base of the Oretian within the uppermost Carnian.
- The Carnian/Norian boundary is assigned an age of 227.0 Ma by Cohen et al. (2014; 228.4 Ma in Gradstein 2012), so we arbitrarily assign a slightly older age of **227.5 Ma** to the base of the Oretian (unchanged from Cooper 2004, 229 Ma in Raine et al. 2012).

6.6 Base Otamitan Stage

- LO of the bivalve *Manticula problematica* in the Taringatura Group section, Otamita Stream, Southland (Cooper 2004).
- The Otamitan Stage was correlated approximately with the *Magnus* and *Rutherfordi* Zones of the boreal ammonoid sequence by J.D. Campbell (1985) and H.J. Campbell (1994). The age calibration of Boreal ammonoid zones presented by Gradstein et al. (2012) suggests that these two zones together span only 1.26 Ma (218.16 - 216.90 Ma), but the stratigraphic thickness of the stage in Murihiku Supergroup sections speaks for a longer duration. In fact, on the basis of its meagre ammonoid fauna, Begg et al. (1983) correlated the lower Otamitan with the Boreal ammonoid *Dawsoni* Zone, an apparently long zone which precedes the *Magnus* Zone. Mundil et

al. (2010) reported a CA-TIMS based U-Pb zircon age of 218 Ma for a tuff intercalated within Otamitan shellbeds of *Manticula problematica*.

- On the basis of the age calibration of Boreal ammonoid zones presented by Gradstein et al. (2012), we calibrate the base of the Otamitan Stage approximately mid-way through the *Dawsoni* Zone, at **221.0 Ma** (217 Ma in Cooper 2004).

6.7 BASE WAREPAN STAGE

- LO of the bivalve *Monotis (Eomonotis) kiritehereensis* in the Murihiku Supergroup coastal section south of Kiritehere Stream, southwest Auckland (Cooper 2004).
- The Warepan Stage is correlated with the *Columbianus* and *Cordilleranus* Zones of the Boreal ammonoid sequence (Grant-Mackie 1985).
- On the basis of the age calibration of Boreal ammonoid zones presented by Gradstein et al. (2012), we calibrate the base of the Warepan Stage at **217.0 Ma** (212.0 Ma in Cooper 2004).

6.8 BASE OTAPIRIAN STAGE

- LO of the brachiopod *Rastelligera diomedea* in the Taringatura Group section, Otapiri Stream, Southland (Cooper 2004).
- The Otapirian Stage has long been correlated with the Rhaetian (Marwick 1953). Since it succeeds the Warepan Stage which is correlated with the *Columbianus* and *Cordilleranus* Zones of the Boreal ammonite succession, a general *Amoenum-Crickmayi* Zone correlation was suggested by Begg et al. (1983) and de Jersey & Raine (1990). A distinct microfloral change, which corresponds to the base of the *Foveosporites moretonensis* Zone of de Jersey & Raine (1990) and includes the appearance of *Classopollis*, occurs in the lower part of the stage. This has a parallel in similar changes which are recorded near the base of the Rhaetian in Europe (e.g. Schuurman 1979).
- We arbitrarily equate the base of the Otapirian Stage with the base of the *Amoenum* Zone and the Rhaetian Stage, which Cohen et al. (2014) calibrate at **208.5 Ma** (204.5 Ma in Cooper 2004, 209.5 Ma in Raine et al. 2012)**.**

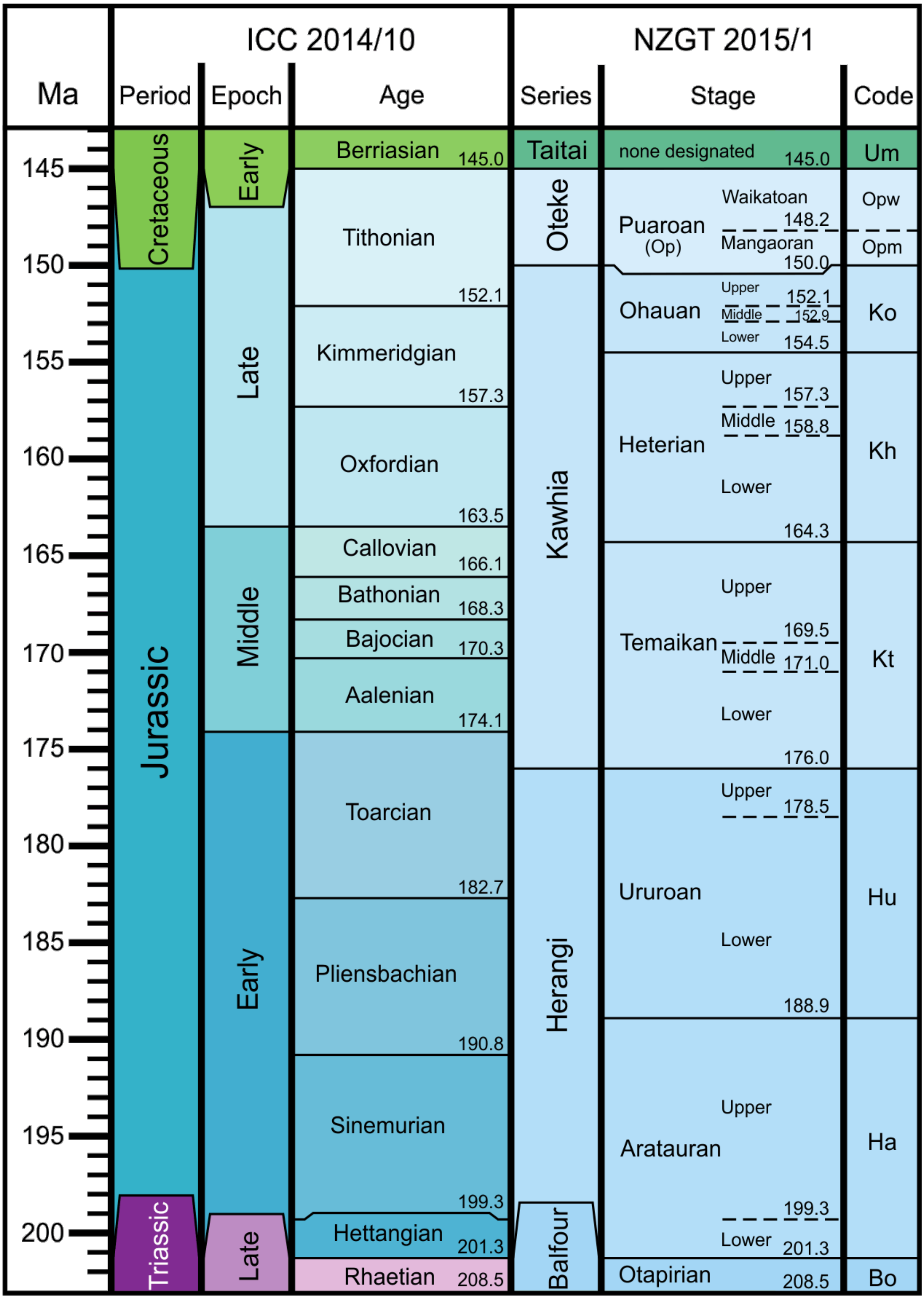

Figure 7 Jurassic Timescale. The 2015 calibration of Oteke to Herangi Series stages with the Global Geochronological Scale for the Jurassic Period, as published in the 2014 International Chronostratigraphic Chart (ICC 2010/10, Cohen et al. 2014).

7.0 JURASSIC

Calibration of the global Jurassic stage boundaries by Cohen et al. (2014) does not differ from that provided by Gradstein et al. (2012), but exhibits minor changes from the version used by Cooper (2004). The NZGT2015/1 calibration is illustrated in Figure 7. In contrast to current New Zealand Cenozoic substages those of the Jurassic are regarded as formally established, although definitions of defining events and their current stratotype locations are here amended for several Jurassic substage boundaries.

7.1 BASE ARATAURAN STAGE, LOWER ARATAURAN SUBSTAGE, HERANGI SERIES, AND BASE OF JURASSIC

- LO of the bivalve *Otapiria marshalli* in the Diamond Peak Group section, Otapiri Stream, Southland (Cooper 2004).
- As discussed by Cooper (2004, p. 96) and Stevens (2004), the LO of *Otapiria marshalli* at Otapiri Stream is about 45 m stratigraphically lower than the lowest known Jurassic ammonite of the New Zealand succession, the lower Hettangian species *Planorbis* cf. *pacificum*, which occurs in the adjacent Taylors Stream section. Following these authors, and recognising that the underlying New Zealand Otapirian Stage is correlated with the Rhaetian, we equate the base of the Aratauran with the Triassic/Jurassic boundary although the precise relationship remains uncertain.
- Gradstein et al. (2012) and Cohen et al. (2014) place the Triassic/Jurassic boundary at **201.3 Ma** (199.6 Ma in Cooper (2004).

7.2 BASE UPPER ARATAURAN SUBSTAGE

- LO of the brachiopod *Herangirhynchia arawheroensis* in the Diamond Peak Group section on Ben Bolt, Otapiri Valley, Southland (Cooper 2004).
- At Ben Bolt, the LO of *H. arawheroensis* is associated with ammonites indicating an earliest Sinemurian correlation (Stevens 2004). The base of the Upper Aratauran is accordingly equated with the base of the Sinemurian.
- Based on the calibration of the Sinemurian in Gradstein et al. (2012) and Cohen et al. (2014), an age of **199.3 Ma** is assigned (c. 197 Ma in Cooper 2004).

7.3 BASE URUROAN STAGE AND LOWER URUROAN SUBSTAGE

- LO of the bivalve *Pseudaucella marshalli* in the Ururoa Shellbed section (now Waitapu Formation - Waterhouse & White, 1994) near Otamaehu Point, Kawhia (Cooper 2004).
- The ammonite *Juraphyllites* ex. gr. *libertus*, which occurs 100 m above the LO of *P. marshalli* in the Ururoa Shellbed, provides a correlative tie-point to the mid-Pliensbachian within the upper part of the Lower Ururoan (Stevens 2012, 2014). Hudson (2003) suggested a Lower Pliensbachian, or possibly Sinemurian correlation for the base of the Ururoan. Here a Lower Pliensbachian position is adopted.
- Based on the calibration of the Pliensbachian in Gradstein et al. (2012) and Cohen et al. (2014), an age of **188.9 Ma** is assigned (188.0 Ma in Cooper 2004).

7.4 BASE UPPER URUROAN SUBSTAGE

- LO of the ammonite *Catacoeloceras grangei* Stevens, 2008 (formerly *Dactylioceras* sp.) in the Ururoa Formation section (now Opango Fm - Waterhouse & White, 1994) near Ururoa Point, Kawhia (Cooper 2004).
- Stevens (2007) recorded a mid-Toarcian (middle *Bifrons* Zone) ammonite *Harpoceras subplanatum* from strata correlated with a Ururoa Formation horizon slightly below the Kawhia "*Dactylioceras* Bed", i.e. uppermost Lower Ururoan. An upper *Bifrons* Zone correlation was suggested for *Catacoeloceras grangei* itself (Stevens 2008).
- Based on the calibration of Toarcian ammonite biozones in Gradstein et al. (2012), an age of **178.5 Ma** is assigned (c. 183.0 Ma in Cooper 2004).

7.5 BASE TEMAIKAN STAGE, LOWER TEMAIKAN SUBSTAGE, AND KAWHIA SERIES

- LO of the belemnite *Belemnopsis deborahae* in the Ohautira Formation section, Opuatia Valley, Port Waikato (Cooper 2004).
- The base of the Temaikan was long correlated by New Zealand authors with the base of the Aalenian, but Hudson (2003) and Challinor & Hudson (2007) suggest that species of the belemnite genera *Dactyloteuthis* and *Brevibelus* present in Lower Temaikan strata provide evidence for an Upper or Middle Toarcian position (using a threefold division of that stage). Here we adopt a compromise basal Upper Toarcian correlation.
- Based on the calibration of Toarcian biozones in Gradstein et al. (2012), an age of **176.0 Ma** is assigned (175.6 Ma in Cooper 2004).

7.6 BASE MIDDLE TEMAIKAN SUBSTAGE

- LO of the bivalve *Retroceramus (Fractoceramus) inconditus* in the Putau Siltstone section, Opuatia Valley, Port Waikato (Cooper 2004).
- Westermann et al. (2000) note that *R. inconditus* is similar to uppermost Aalenian and Lower Bajocian taxa from the Northern Hemisphere and Argentina. Hudson (2003) adopted an upper Aalenian correlation for the base of the substage and this position is followed here.
- Based on the calibration of the Aalenian in Gradstein et al. (2012) and Cohen et al. (2014), an age of **171.0 Ma** is assigned (c.172 Ma in Cooper 2004).

7.7 BASE UPPER TEMAIKAN SUBSTAGE

- LO of the bivalve *Retroceramus marwicki* in the Wilson Sandstone section, Opuatia Valley, Port Waikato (Cooper 2004).
- *R. marwicki* is known from the lower Upper Bajocian (*Niortense* Zone) in Argentina (Damborenea 1990, Damborenea & Manceñido 1992). Ammonites from the upper part of the Middle Temaikan Substage (*Chondroceras* spp.) suggest an upper Lower Bajocian correlation (*Humphresianum* Zone). The base of the Upper Temaikan is therefore correlated with the base of the Upper Bajocian, and the substage embraces topmost Bajocian, Bathonian and most of Callovian time.
- Based on the calibration of Bajocian biozones in Gradstein et al. (2012), an age of **169.5 Ma** is assigned (169 Ma in Cooper 2004).

7.8 BASE HETERIAN STAGE AND LOWER HETERIAN SUBSTAGE

- LO of the bivalve *Retroceramus galoi* within the Oraka Sandstone section, eastern Totara Peninsula, south Kawhia Harbour (Cooper 2004). Cooper (2004, p. 98) placed this at locality R15/f213, 23 m above the base of the formation, but Westermann et al. (2002) cite possible specimens from R15/f52, only a few metres above the base of the Oraka Sandstone.
- Stevens (1997) suggested the Oraka Sandstone at Kawhia is a condensed sequence spanning the Upper Bathonian to Lower Kimmeridgian. Westermann et al. (2002) revised ammonite faunas from the Oraka Sandstone and adjacent formations, and concluded that the Kawhia section of the unit is restricted to the uppermost Bathonian and Lower Callovian. Hudson (2003) preferred a Middle Callovian correlation for the base of the Heterian, taking into consideration richer ammonite faunas from Awakino, as well as international correlation of the Temaikan-Heterian *Retroceramus* sequence and dinoflagellate data from the Kawhia section (Helby et al. 1988). This position is adopted here.
- The Lower Heterian Substage spans the Callovian-Oxfordian boundary, which is calibrated at 163.5 Ma by Gradstein et al. (2012) and Cohen et al. (2014). Based on the calibration of Callovian biozones in Gradstein et al. (2012), an age of **164.3 Ma** is assigned to the base of the stage (157.5 Ma in Cooper 2004).

7.9 BASE MIDDLE HETERIAN SUBSTAGE

- LO of the bivalve *Malayomaorica malayomaorica* in the Captain Kings Shellbed section, eastern Totara Peninsula, south Kawhia Harbour (MacFarlan 1998; Cooper 2004).
- The Middle Heterian Substage is represented by the Captain Kings Shellbed and most of the overlying Ohineruru Formation. Correlation of this substage with international stages is based on ammonite and belemnite fossils (Stevens 1997; Westermann et al. 2002; Challinor 2003).
- The base of the Middle Heterian Substage is within the Oxfordian and is arbitrarily calibrated at **158.8 Ma** (156.0 Ma in Cooper 2004).

7.10 BASE UPPER HETERIAN SUBSTAGE

- LO of the bivalve *Retroceramus subhaasti* in the Ohineruru Formation in the Heteri Peninsula section, south Kawhia Harbour (Challinor 2003). This replaces the earlier definition of Cooper (2004) which has proved unsatisfactory because of difficulty with taxonomic identification of *Retroceramus cf. galoi*.
- The Upper Heterian Substage is represented by topmost Ohineruru Formation and the overlying Kiwi Sandstone and Waikutakuta Siltstone (Challinor 2003).
- The base of the Upper Heterian Substage is arbitrarily correlated with the Oxfordian-Kimmeridgian boundary, which is calibrated at **157.3 Ma** by Gradstein et al. (2012) and Cohen et al. (2014) (155.0 Ma in Cooper 2004).

7.11 BASE OHAUAN STAGE AND LOWER OHAUAN SUBSTAGE

- LO of the bivalve *Retroceramus haastii* in the Waikiekie Tuffaceous Sandstone section along Whakapirau Road, south Kawhia Harbour (Cooper 2004).

- The base of the stage is correlated with the mid-Kimmeridgian on ammonites (Stevens 1997).
- Based on the calibration of Kimmeridgian biozones in Gradstein et al. (2012), an age of **154.5 Ma** is assigned (153.5 Ma in Cooper 2004)

7.12 BASE MIDDLE OHAUAN SUBSTAGE

- HO of the bivalve *Retroceramus haasti* in the Lemon Point Road section, southern Kawhia (Meesook & Grant-Mackie 1995)
- In Cooper (2004) the base of the Middle Ohauan was defined by the highest occurrence of *Malayomaorica malayomaorica*; here we revert to the original definition of Meesook & Grant-Mackie (1995), who state that the HO of *M. malayomaorica* approximates that of *R. haastii* in south Kawhia, but that *M. malayomaorica* ranges higher in the north Kawhia-Port Waikato region. The Middle Ohauan Substage includes the uppermost 30 m of the Kowhai Point Siltstone and the lower part of the Takatahi Formation within the Lemon Point Road section (Meesook & Grant-Mackie 1995).
- The base of the Middle Ohauan Substage is correlated within the upper Kimmeridgian and calibrated at 152.9 Ma (152.2 Ma in Cooper 2004).

7.13 BASE UPPER OHAUAN SUBSTAGE

- LO of the belemnite *Belemnopsis trechmanni* at R15/f171 (Challinor 1996; not R16/f239 as stated in Cooper 2004, p. 100), in the Takatahi Formation coastal section at Ohaua Point, south Kawhia (Meesook & Grant-Mackie 1995; Challinor 2003; Cooper 2004).
- The *Belemnopsis trechmanni* Zone is at least 1100 m thick in the Lemon Point Road section, south Kawhia, and is represented by the middle and upper Takatahi Formation and most of the Kinohaku Siltstone (Meesook & Grant-Mackie 1995).
- The base of the Upper Ohauan Substage is correlated with the Kimmeridgian-Tithonian boundary, which is calibrated by Gradstein et al. (2012) and Cohen et al. (2014) at **152.1 Ma** (150.75 Ma in Cooper 2004).

7.14 BASE PUAROAN STAGE, MANGAORAN SUBSTAGE, AND OTEKE SERIES

- LO of the belemnite *Hibolithes arkelli* in basal strata of the Lower Puti Siltstone section at Moewaka Stream, Port Waikato (Cooper 2004). This locality is R13/f6982 (Challinor 2001, p. 225), not R13/f6981 as stated in Cooper (2004, p.100).
- Comparison of belemnite sequences led Challinor (2001) to conclude that the LO of *H. arkelli* at Port Waikato is approximately correlative with that at Kawhia Harbour, but there it lies within the uppermost Kinohaku Siltstone. Associated ammonites in both sequences (Stevens 1997) suggest correlation with the Middle Tithonian (*Semiforme* Zone).
- Based on the calibration of Tithonian biozones in Gradstein et al. (2012) and Cohen et al. (2014), an age of **150.0 Ma** is assigned (148.5 Ma in Cooper 2004).

7.15 BASE WAIKATOAN SUBSTAGE OF PUAROAN STAGE

- LO of the belemnite *Belemnopsis aucklandica* in basal beds of the Upper Puti Siltstone section at Okahu Stream, Port Waikato (Cooper 2004).
- Challinor (2001) showed that the LO of *B. aucklandica* at Port Waikato lies within the biozone of the bivalve *Buchia* aff. *misolica*, and is stratigraphically above the highest local occurrence of the ammonite *Aulacosphinctoides brownei* (Middle Tithonian: Stevens 1997), but below occurrences of the ammonites *Subplanites huriwaiensis* and *Subdichotomoceras maraetaiensis* (Late Tithonian: Stevens 1997). An upper Middle Tithonian (upper *Fallauxi* Zone) correlation is adopted for the base of the Waikatoan. By convention, the Waikatoan Stage is of uppermost Jurassic age and extends only up to the base of the Cretaceous.
- Based on the calibration of Tithonian biozones in Gradstein et al. (2012) and Cohen et al. (2014), an age of **148.2 Ma** is assigned (c. 146.8 Ma in Cooper 2004).

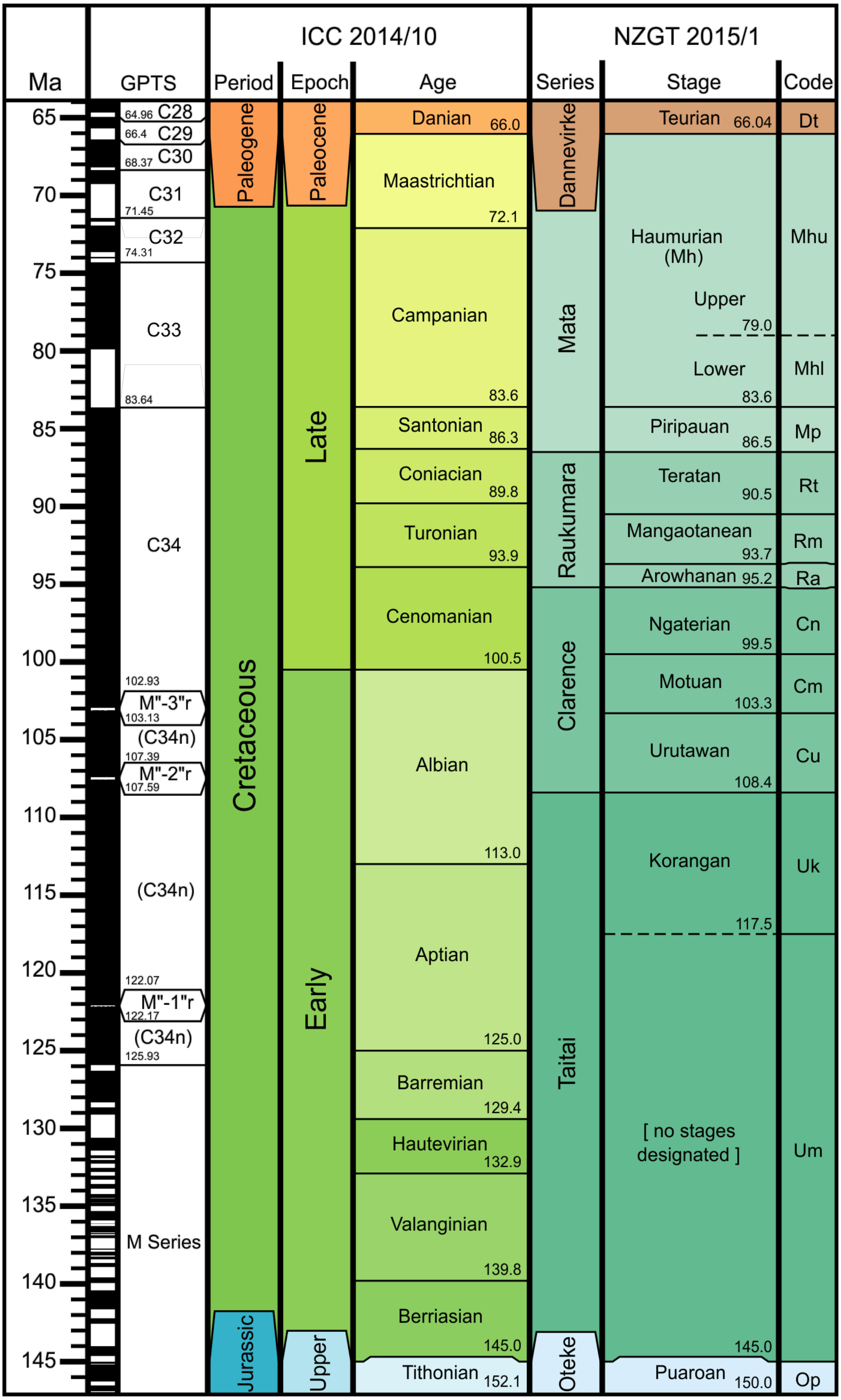

Figure 8 Cretaceous Timescale.The 2015 calibration of Mata to Taitai Series stages with the revised Geomagnetic Polarity Timescale (GPTS, after Gradstein et al. 2012) and Global Geochronological Scale, as published in the 2014 International Chronostratigraphic Chart (ICC 2010/10, Cohen et al. 2014).

8.0 CRETACEOUS

The ages assigned to lower boundaries of Cretaceous stages by Cohen et al. (2014) agree with those provided by Gradstein et al. (2012) for the Albian and younger stages. The ages differ for the Valanginian to Aptian stages, but the only New Zealand stage potentially affected is the Korangan. The correlation of the Korangan fauna is so imprecisely known that no change in age calibration is warranted. The new calibration is illustrated in Figure 8.

8.1 BASE TAITAI SERIES AND BASE CRETACEOUS

- LO of the spore *Ruffordiaspora australiensis* in New Zealand sections (informal); no SSP defined.
- The base of the Taitai Series is taken, by convention, to correspond to the Jurassic/Cretaceous boundary. Correlation of the lowest occurrence of *R. australiensis* to the Jurassic/Cretaceous boundary is approximate and untested in New Zealand, although widely used in this context in Australia (Monteil 2006).
- Cohen et al. (2014) place the Jurassic/Cretaceous boundary at **145.0 Ma** (145.5 Ma in Cooper 2004 and Hollis et al. 2010).

8.2 BASE KORANGAN STAGE

- Base of the macrofossil *Aucellina* cf. *radiatostriata* Assemblage Zone (informal); no SSP defined.
- Calibration very poorly constrained; by interpolation from the base of the Cretaceous and correlation of the *A.* cf. *radiatostriata* Zone fauna (Cooper 2004).
- Boundary provisionally placed at **117.5 Ma** (unchanged from Cooper 2004 and Hollis et al. 2010).

8.3 BASE URUTAWAN STAGE AND CLARENCE SERIES

- LO of the inoceramid bivalve *Mytiloides ipuanus* in the Motu Falls Section.
- Calibration very poorly constrained; by interpolation and based on radiometric dates derived from Motuan and Ngaterian volcanic rocks, and correlation of the macrofossil *Aucellina* cf. *gryphaeoides* Assemblage Zone fauna (Cooper 2004).
- Boundary placed at **108.4 Ma** (unchanged from Cooper 2004 and Hollis et al. 2010).

8.4 BASE MOTUAN STAGE

- LO of the aucellinid bivalve *Aucellina euglypha* in the Motu Falls section, Raukumara Peninsula (Cooper 2004).
- Calibration by interpolation and based, in particular, on a revised radiometric age for zircons from a middle Motuan tuff bed in the Motu Falls section (Crampton et al. 2004): three new, high-precision Chemical Abrasion-TIMS single zircon analyses yield an age of 101.24 ± 0.17 Ma (MSWD 0.80) (pers. comm. J. Ramezani, November 2012). Other biostratigraphic constraints are listed in Cooper (2004).
- Boundary placed at **103.3 Ma** (unchanged from Cooper 2004 and Hollis et al. 2010).

8.5 BASE NGATERIAN STAGE

- LO of the inoceramid bivalve "*Inoceramus*" *tawhanus* in the "Te Waka Stream" section, Raukumara Peninsula (Cooper 2004).
- Calibration by interpolation and based, in particular, on a 96.1 ± 0.6 Ma radiometric age (Cooper 2004) for an upper Ngaterian basalt in the Clarence valley, Marlborough, and a 101.24 ± 0.17 Ma radiometric age for a middle Motuan tuff (see above).
- Boundary placed at **99.5 Ma** (100.2 Ma in Cooper 2004 and Hollis et al. 2010).

8.6 BASE AROWHANAN STAGE AND RAUKUMARA SERIES

- LO of the inoceramid bivalve *Magadiceramus rangatira haroldi* in the Mangaotane Stream section, Raukumara Peninsula (Cooper 2004).
- Calibration by interpolation and based on the age assigned to the base of the Mangaotanean Stage (see below) and radiometric dating of Ngaterian basalt (see above); supported by upper Cenomanian correlation (Partridge 2006) of the HO of the dinoflagellate *Lithosphaeridium siphoniphorum glabrum*, which is in the upper part of the Arowhanan, and other dinoflagellate correlations (Schiøler & Crampton 2014). The base of the stage coincides closely with the *Ascodinium serratum* interval dinoflagellate zone of Schiøler & Crampton (2014).
- Boundary placed at **95.2 Ma** (unchanged from Cooper 2004 and Hollis et al. 2010).

8.7 BASE MANGAOTANEAN STAGE

- LO of the inoceramid bivalve *Cremnoceramus bicorrugatus matamuus* in the Mangaotane Stream section, Raukumara Peninsula (Cooper 2004).
- A positive stable carbon isotope excursion is observed in the uppermost part of the Arowhanan Stage in the Sawpit Gully section, Marlborough, and is correlated with the Cenomanian/Turonian boundary (CTB) carbon isotope excursion (Hasegawa et al. 2013). Based on inoceramid bivalve, dinoflagellate, and lithostratigraphic correlations, the CTB is constrained to lie within an interval 220-235 m above the base of the Arowhanan Stage in its boundary stratotype section in Mangaotane Stream, and about 10-25 m below the boundary stratotype of the Mangaotanean Stage (Hasegawa et al. 2013; these stratigraphic heights account for the fact that the base of the measured section given in Hasegawa et al. lies 10 m above the base of the Arowhanan Stage as defined in Crampton et al. 2001). Thus, assuming constant sedimentation rates through the Arowhanan in Mangaotane Stream (a reasonable assumption given the uniformity of lithology) and ignoring some probably minor structural complication, we infer that the Cenomanian/Turonian boundary correlates with a level in the upper 90-95% of the Arowhanan Stage.
- Cohen et al. (2014) place the Cenomanian/Turonian boundary at 93.9 Ma; here we adopt an age of **93.7 Ma** for the base of the Mangaotanean Stage (92.1 Ma in Cooper 2004, 93 Ma in Hollis et al. 2010).

8.8 BASE TERATAN STAGE

- LO of the bivalve *Inoceramus opetius* in the Mangaotane Stream section, Raukumara Peninsula (Cooper 2004).

- Calibration by interpolation and based on events listed below for the Piripauan Stage, as well as: the HO of the dinoflagellate *Sepispinula ambigua* in the upper Teratan (Schiøler & Wilson 1998, Crampton et al. 2001), which is inferred to be upper Coniacian in Australia (Helby et al. 1987); and the LO of the dinoflagellate *Conosphaeridium striatoconum* in the middle Teratan (Schiøler & Wilson 1998, Crampton et al. 2001), which is mid-Coniacian in Australia (Helby et al. 1987, Partridge 2006). Other relevant events detailed in Cooper (2004) include the range of *Inoceramus*? *madagascariensis,* and the HO of *Hedbergella planispira* near the top of the underlying Mangaotanean Stage).
- Boundary placed at **90.5 Ma** (89.1 Ma in Cooper 2004, 88.6 in Hollis et al. 2010).

8.9 BASE PIRIPAUAN STAGE AND MATA SERIES

- LO of the bivalve *Inoceramus pacificus* in the Ben More Stream section, Marlborough (Cooper 2004).
- Calibration by interpolation and based, in particular, on the following criteria: the age of the C34/C33 chron boundary (see below); correlation of the underlying Teratan Stage; the mid-Piripauan (Schiøler & Wilson 1998, Schiøler et al. 2000) and mid-Santonian correlation (Helby et al. 1987, Partridge 2006) of the LO of the dinoflagellate *Isabelidinium cretaceum*; and the highest *consistent* occurrence of the dinoflagellate *Conosphaeridium striatoconum* in the lowest Piripauan (Schiøler & Wilson 1998), which is inferred to have an earliest Santonian age in Australia (Helby et al. 1987, Partridge 2006).
- Boundary placed at **86.5 Ma** (unchanged from Cooper 2004 and Hollis et al. 2010).

8.10 BASE HAUMURIAN STAGE AND LOWER HAUMURIAN SUBSTAGE

- LO of the dinoflagellate cyst *Nelsoniella aceras* in the Ben More Stream section, Marlborough (Cooper 2004).
- The boundary is inferred to lie at, or very close to, the base of Chron C33 in the Ben More Stream section. Additional evidence used for correlation is the LO of the dinoflagellate *Xenikoon australis* (Roncaglia et al. 1999), which occurs within the lower part of the Lower Haumurian and is dated as Early Campanian in Australia (Helby et al. 1987, Partridge 2006).
- Gradstein et al. (2012) correlate the C33/C34 chron boundary with the base of the Campanian. Adopting this correlation, we assign an age of **83.6 Ma** for the base of the Haumurian Stage (84.0 Ma in Cooper 2004, 83.5 Ma in Hollis et al. 2010).

8.11 BASE UPPER HAUMURIAN SUBSTAGE

- LO of the dinoflagellate cyst *Isabelidinium pelludicum* in the Conway River railway cutting section, northern Canterbury (Cooper 2004). This is a formally established subdivision of the Haumurian Stage (Crampton et al. 2000).
- A revised calibration from that given in Cooper (2004) is based on the inferred mid-Campanian age of the LO of *I. pellucidum* in New Zealand (Crampton et al. 2006) and Australia (Marshall 1985, Helby et al. 1987, Partridge 2006), and by interpolation using the ages of the K/Pg boundary and the C34/C33 chron boundary.
- Boundary placed at **79 Ma** (74.5 Ma in Cooper 2004 and Hollis et al. 2010).

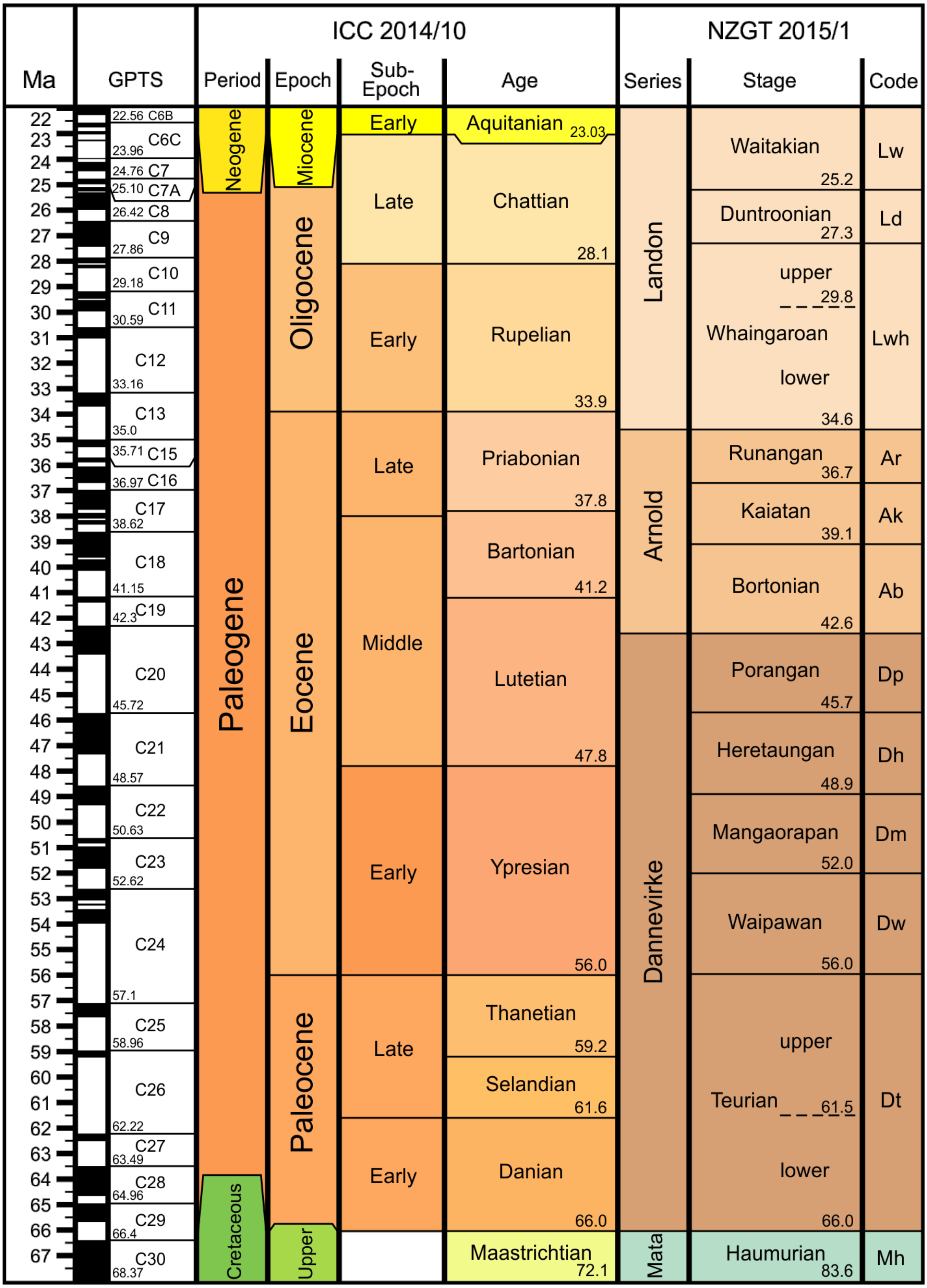

Figure 9 Paleogene Timescale. The 2015 calibration of Landon to Dannevirke Series stages with the revised Geomagnetic Polarity Timescale (GPTS, after Gradstein et al. 2012) and Global Geochronological Scale for the Paleogene Period, as published in the 2014 International Chronostratigraphic Chart (ICC 2010/10, Cohen et al. 2014).

9.0 PALEOGENE

The calibration of international stage boundaries by Cohen et al. (2014) is identical to that of Gradstein et al. (2012). The calibration of New Zealand stages is shown in Figure 9.

9.1 BASE TEURIAN STAGE, DANNEVIRKE SERIES, AND BASE PALEOGENE

- The stage was originally defined on the basis of a foraminiferal assemblage in the unit stratotype section at Te Uri Stream, southern Hawkes Bay (Finlay & Marwick 1947). It was later recognised that the base of the stage corresponds to the Cretaceous-Paleogene (K-Pg) boundary, and that Te Uri Stream section is unsuitable for a boundary SSP because it lacks evidence for a complete K-Pg boundary, namely a distinctive basal Paleocene foraminiferal assemblage consisting of small planktic species, including Cretaceous survivors such as *Guembelitria cretacea*, and a geochemical anomaly, shown primarily by enrichments in iridium and nickel (Hollis 2003). The Flaxbourne River section in Chancet Quarry, Ward, eastern Marlborough has been designated as the boundary SSP (Cooper 2004) because all components of an intact K-Pg boundary transition are present there (Strong 2000).
- The K-Pg boundary and hence the base of the Teurian is now dated at 66.04 Ma (Gradstein et al. 2012), rounded here to **66.0 Ma** following Cohen et al. (2014; 65.0 Ma in Cooper 2004, 65.5 Ma in Hollis et al. 2010).

9.2 BASE UPPER TEURIAN SUBSTAGE (INFORMAL)

- LO of the calcareous nannofossil species *Fasciculithus tympaniformis* (base of zone NP5). No SSP has been defined.
- Cyclostratigraphy (Schmitz et al. 2011) indicates the FAD of *F. tympaniformis* is about 0.1 My above the base of the international Selandian Stage, which is approximately at the top of the lower third of Chron C26r and is dated by Gradstein et al. (2012) at 61.61 Ma. Thus the age of the base of the upper Teurian is placed at **61.5 Ma**.

9.3 BASE WAIPAWAN STAGE

- Originally based on the HO of *Stensioina beccariformis* and several other species of benthic foraminifera that are inferred to have died out in response to a global event, the Paleocene-Eocene thermal maximum (PETM). The negative carbon isotope excursion (CIE) that marks the base of this event has been adopted as the principal criterion for recognising the Paleocene-Eocene boundary internationally (Luterbacher et al. 2000; Aubry et al. 2003). The CIE is now used also in New Zealand as the principal criterion for recognition of the Teurian-Waipawan boundary (Cooper 2004), equivalent to the base of the Eocene (Berggren et al. 1995). Because of poor exposure at the original unit stratotype section, Te Uri Stream, a new boundary SSP was defined at Tawanui, Hawkes Bay, approximately 11 km southwest of Te Uri Stream (Cooper 2004).
- As the age of the base of the Eocene has been revised to 55.96 Ma by Gradstein et al. (2012), rounded to **56.0 Ma** in Cohen et al. (2014), this is also the revised age for the base of the Waipawan (55.5 Ma in Cooper 2004, 55.8 Ma in Hollis et al. 2010).

9.4 BASE MANGAORAPAN STAGE

- LO of the planktic foraminifera *Morozovella crater* (Cooper 2004). Because of poor exposure at the unit stratotype section, Te Uri Stream, Hawkes Bay, a new boundary SSP is needed.
- The LO of the nannofossil *Discoaster lodoensis* has been previously cited as occurring just above the base of the stage in the Waipawa parastratotype section, Hawkes Bay (Edwards 1971), and the age of this datum at tropical/subtropical locations was used by Cooper (2004), Hollis et al. (2010) and Raine et al. (2012) to calibrate the base of the Mangaorapan. The FAD of *D. lodoensis* was placed within Chron C24n.2r by Berggren et al. (1995a), but at the mid-point of Chron C24n.3n (53.70 Ma) by Gradstein et al. (2012). However, the precise relationship between the LO of *M. crater* and that of *D. lodoensis* in New Zealand sections remains uncertain.

  Original sampling of the Te Uri and Waipawa sections was coarse and the sections are no longer available. In the detailed magnetostratigraphic-biostratigraphic study at Mead Stream in Marlborough (Dallanave & Agnini et al. 2014), using a corrected range of *M. crater* by C.P. Strong (pers. comm. 2014), the LO of *M. crater* lies in the upper part of the Lower Marl, between 262.96 m (C23r.89, 51.91 Ma) and 279.3 m (base C23n.1r, 50.96 Ma), over 40 m higher than the LCO of *D. lodoensis* which is reported between 220.42 and 222.12 m (C24n.1n.33, 52.92 Ma). The magnetostratigraphic dating at Mead Stream is consistent with the $\delta^{13}C$ profile, which places the LO of *M. crater* well above the "K/X" event (221-224.6 m, Slotnick et al. 2012). In the mid-Waipara section the LO of *M. crater* is recorded c.1.1 m below the LO of *D. lodoensis* (Hollis et al. 2012, Shepherd et al. 2014, C. Shepherd pers. comm. 2014). This horizon is about 10 m below the c. 40 m section studied by Dallanave & Bachtadse et al. (2014), but also within the apparently lithologically uniform Ashley Mudstone; linear extrapolation of their upper Mangaorapan to Heretaungan age-deposition relationship, which is well-constrained by magnetostratigraphy and biostratigraphy, suggests that the LO of *M. crater* in this section corresponds to c. 52.0 Ma.
- The apparent age of the LO of *M. crater* at mid-Waipara (52.0 Ma) is similar to the earlier limit of the possible age range at Mead Stream (51.9 Ma). Since these calibrations derive from well-studied New Zealand sections in different sedimentary basins, a provisional age of **52.0 Ma** is preferred over the previous proxy calibration based on the FAD of *Discoaster lodoensis* in lower paleolatitudes (53.0 Ma in Cooper 2004, 53.3 Ma in Hollis et al. 2010, 53.7 Ma in Raine et al. 2012).

9.5 BASE HERETAUNGAN STAGE

- LO of the benthic foraminifera *Elphidium hampdenense*. Because of poor exposure at the unit stratotype section, Te Uri Stream, Hawkes bay, a new boundary SSP is needed.
- In recent magnetostratigraphic-biostratigraphic work (Dallanave & Bachtadse et al. 2014; Dallanave & Tauxe et al., submitted), the LO of *E. hampdenense* is located in the Middle Waipara River section, north Canterbury, at a position corresponding to Chron C22n.6. The LO of the nannofossil *Discoaster sublodoensis*, which occurs near the top of the underlying Mangaorapan Stage and is used as a secondary datum, occurs within the Middle Waipara River section at approximately C22n.3. The FAD of *D. sublodoensis* was placed at the base of Chron C22n by Berggren et al. (1995a), but at C22n.3 by Gradstein et al. (2012).

- The Waipara River position of the LO of *E. hampdenense* equates to an age of 48.9 Ma and the LO of *D. sublodoensis* to 49.1 Ma, using the calibration of Chron C22n by Gradstein et al. (2012). Accepting the Waipara data, the age of the base of the Heretaungan is **48.9 Ma** (49.5 Ma in Cooper 2004, 49.3 Ma in Hollis et al. 2010, 49.2 Ma in Raine et al. 2012).

9.6 BASE PORANGAN STAGE

- LO of the benthic foraminifera *Elphidium saginatum* is the primary datum. HO of the planktic foraminifera *Morozovella crater*, which occurs in the latest Heretaungan Stage, is a useful secondary datum. Because of poor exposure at the unit stratotype section, Te Uri Stream, Hawkes Bay, a new SSP is needed.
- The LAD of *M. crater* is poorly defined due to sporadic records beyond the New Zealand region, possibly related to difficulties in distinguishing *M. crater* from similar species (*M. aragonensis*, *M. formosa*). Edwards et al. (1988) used the last sporadic occurrence of *M. crater* in DSDP hole 516F, just above the base of Chron C20, as the datum for calibration. The base of C20r was calibrated at 45.72 Ma by Gradstein et al. (2012) and the base of the Porangan is therefore placed at **45.7 Ma** (46.2 Ma in Cooper 2004, 45.3 Ma in Hollis et al. 2010).

9.7 BASE BORTONIAN STAGE AND ARNOLD SERIES

- LO of the planktic foraminifera *Globigerinatheka index* in the Hampden coastal section, north Otago, which was defined as the boundary SSP by Morgans (2009).
- The FAD of *G. index* occurs near the C20n/C20r chron boundary (Berggren et al. 1995a). Gradstein et al. (2012) chron-scaled the Berggren et al. (1995a) age of 42.9 Ma as C20n.7, giving a revised age of 42.64 Ma based on their calibration for Chron C20n at 42.30–43.43 Ma. The base of the Bortonian is accordingly placed at **42.6 Ma**. (43.0 Ma in Cooper 2004, 42.77 Ma in Hollis et al. 2010).

  Note: The FAD of *G. index* occurs in the upper part of Eocene zone E9 (Berggren & Pearson 2005), and defines the base of Antarctic planktic foraminiferal zone AE6, which was placed at the C20n/C20r chron boundary by Huber & Quillevere (2005).

9.8 BASE KAIATAN STAGE

- Originally defined on the HO of the benthic foraminifera *Bulimina bortotara* and for calibration purposes tied to the LO of the nannofossil *Chiasmolithus oamaruensis*, the stage lacked a stratotype section or an SSP (Cooper 2004). Morgans (2009) redefined the base of the Kaiatan as the HO of the planktic foraminifera *Acarinina primitiva* in the Hampden coastal section, north Otago.
- Berggren et al. (1995a) placed the LAD of *Acarinina primitiva* in the middle of Chron C18n, at a position equivalent to C18n.1n.5. Based on the revised age range of 38.62–39.63 Ma for Chron C18n.1n (Gradstein et al. 2012), the interpolated age for the LAD of *A. primitiva* and the base of the Kaiatan is placed at **39.1 Ma** (37.0 Ma in Cooper 2004, but on different criteria; 39.0 Ma in Morgans 2009; 38.4 Ma in Hollis et al. 2010).

9.9 BASE RUNANGAN STAGE

- LO of the benthic foraminifera *Bolivina pontis* in the Point Elizabeth coastal section, Westland (Cooper 2004).
- There are no planktic foraminiferal datums at this stage boundary, so the age is bracketed by two nannofossil events: the LO of *Isthmolithus recurvus* in the upper Kaiatan and the HO of *Reticulofenestra reticulata* in the lower Runangan.
- The FAD of *Isthmolithus recurvus* was placed by Berggren et al. (1995a) within Chron C16n.2n but by Backman (1987) at the base of C16r, now dated as 36.97 Ma by Gradstein et al. (2012). The LAD of *Reticulofenestra reticulata* has been recorded within Chron C16n.2n at southern high latitude ODP sites 689, 690, 744, 748 and 703; scaling of the Berggren et al. (1995a) position at C16.2n.4 yields a revised age of 36.44 Ma. The base of the Runangan is placed midway between these horizons, at **36.7 Ma** (36.0 Ma in Cooper 2004 and Hollis et al. 2010, 36.4 Ma in Raine et al. 2012).

9.10 BASE WHAINGAROAN STAGE AND LANDON SERIES

- HO of the planktic foraminifera *Globigerinatheka index* at Point Elizabeth, Westland. This section is recognised as the boundary SSP because it is the type section for the underlying Runangan stage (Cooper 2004).
- Berggren et al. (1995a) placed the LAD of *G. index* in the lower part of Chron C13r, based on records from Italy and Kerguelen Plateau ODP Site 748, but noted an earlier LAD in C15n in Weddell Sea ODP drillhole 689n. As there is no Chron C14, the age difference between these records is minimal; the younger age of 34.3 Ma, equivalent to C13r.3, was adopted by Cooper (2004). The age range for C13r has been revised from 33.54-34.67 Ma (Berggren et al. 1995a) to 33.71-35.0 Ma (Gradstein et al. 2012), therefore the interpolated age for this event is now **34.6 Ma** (34.5 Ma in Hollis et al. 2010).

  Note: Gradstein et al. (2012) report that the LAD of *G. index* coincides with the LAD of the nannofossils *Discoaster saipanensis* and *Discoaster barbadoensis* and with the lower of three normal “events” in Chron C13r in the Contessa Highway section, Italy (Nocchi et al. 1986, Premoli-Silva et al. 1988).

9.11 BASE UPPER WHAINGAROAN SUBSTAGE (INFORMAL)

- HO of the planktic foraminifera *Subbotina angiporoides*. Although in wide use, this boundary has not yet been formalised (Cooper 2004).
- Berggren et al. (1995a) placed the LAD of *S. angiporoides* in the early part of Chron C11n in DSDP hole 516F and ODP holes 748b, 689b and 690b, dating it at 30.0 Ma. Following Gradstein et al. (2012), the revised age of this horizon, a level equivalent to Chron C11n.2n.3, is 29.84 Ma. This is rounded to **29.8 Ma** (30.0 Ma in Cooper 2004, 30.1 Ma in Hollis et al. 2010).

9.12 BASE DUNTROONIAN STAGE

- LO of the benthic foraminifera *Notorotalia spinosa.* The original type locality was in the northern branch of Landon Creek, north Otago. A more complete, replacement stratotype section in upper Landon Creek was adopted by Hornibrook et al. (1989) but this region is now judged unsuitable for the SSP because of the presence of widespread unconformities and condensed intervals; further work to identify a suitable SSP is required (Cooper 2004).

- Revised strontium dating at Squires Farm (based on Fulthorpe et al. 1996) provides an age of **27.3 Ma** (unchanged from Cooper 2004 and Hollis et al. 2010).

9.13 BASE WAITAKIAN STAGE

- LO of the planktic foraminifera *Globoquadrina dehiscens* at Trig Z, Otiake, Waitaki Valley, north Otago (SSP, Cooper 2004).
- Strontium isotope dating at Trig Z (Graham et al. 2000) provides an age of **25.2 Ma** (unchanged from Cooper 2004 and Hollis et al. 2010).

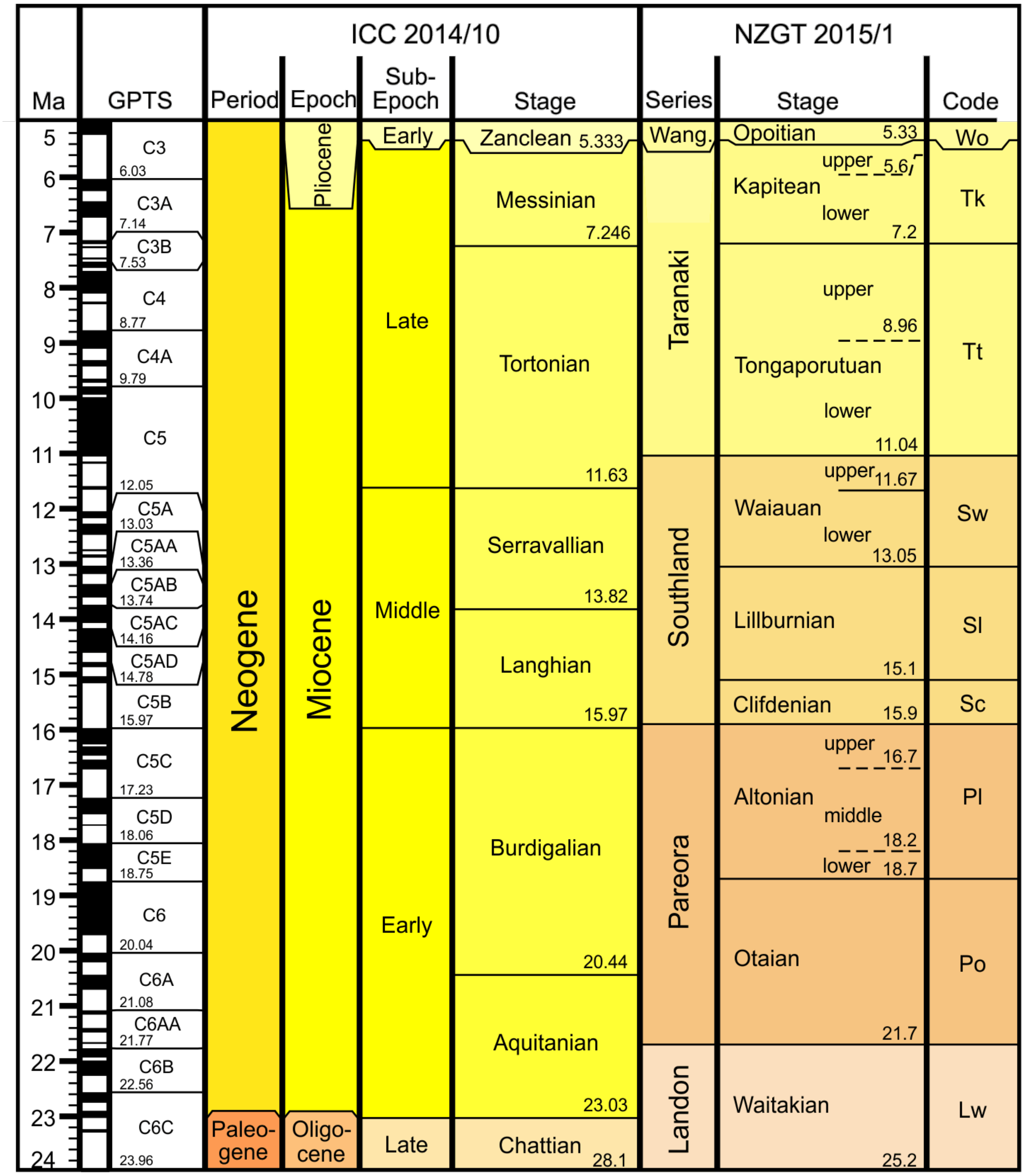

Figure 10 Miocene Timescale. The 2015 calibration of Taranaki to Landon Series stages with the revised Geomagnetic Polarity Timescale (GPTS, after Gradstein et al. 2012) and Global Geochronological Scale for the Miocene Epoch, as published in the 2014 International Chronostratigraphic Chart (ICC 2010/10, Cohen et al. 2014).

10.0 NEOGENE AND QUATERNARY

The base of the of the Quaternary Period, and of the Pleistocene Epoch, was lowered to the base of the Gelasian Stage following formal ratification by the International Union of Geological Sciences (IUGS) in June 2009 (Gibbard et al. 2010). The base of the Gelasian corresponds to Marine Isotope Stage 103, and has an astronomically tuned age of 2.58 Ma (Cohen et al. 2014). Slight differences exist between Cohen et al. (2014) and Gradstein et al. (2012) in calibration of the lower boundaries of the Quaternary stages Calabrian (1.80 Ma versus 1.81 Ma for the latter) and Gelasian (2.58 Ma versus 2.59 Ma). These changes (which may be simply rounding differences) do not appear to affect calibration of the New Zealand stage boundaries (Figure 10 and Figure 11).

10.1 BASE OTAIAN STAGE AND PAREORA SERIES

- LO of the benthic foraminifera *Ehrenbergina marwicki* group at Blue Cliffs, Otaio River, south Canterbury (Cooper 2004). The SSP has not yet been formalised (Cooper 2004).
- Strontium isotope dating at Blue Cliffs (Morgans et al. 1999) provides an age of **21.7 Ma** (unchanged from Cooper 2004 and Hollis et al. 2010).

10.2 BASE ALTONIAN STAGE

- LO of the planktic foraminifera *Globoconella praescitula* is provisionally used as the primary datum. Because there is an unconformity at the base of the unit stratotype section at Clifden, Southland (which lies within the middle Altonian as now defined), a new definition and SSP are needed (Cooper 2004).
- Reported by Berggren et al. (1995a) to occur within lowermost Chron C5En in ODP hole 516F, although a slightly younger age of 18.26 Ma (C5En.5) is given for the datum in Gradstein et al. (2012). However, Morgans et al. (2002) report the event within lowermost Chron C5Er (18.524 - 18.748 Ma; Gradstein et al. 2012) at Tangakaka Stream, which suggests an age of **18.7 Ma**, here adopted for the base of the Altonian (19.0 Ma in Cooper 2004 and Hollis et al. 2010).

10.3 BASE MIDDLE ALTONIAN SUBSTAGE (INFORMAL)

- LO of the planktic foraminifera *Globoconella zealandica.* No SSP has been defined.
- Reported within upper Chron C5Dn in ODP hole 747A in the Kerguelen Plateau (Berggren et al. 1995a), indicating an age of 17.26 Ma (Gradstein et al. 2012). However Morgans et al. (2002) report a significantly earlier position for this event in the upper part of Chron C5En at Tangakaka Stream, East Cape. Based on the age range of 18.056 - 18.524 Ma for Chron C5En (Gradstein et al. 2012), the base of the middle Altonian is placed at **18.2 Ma** (18.5 Ma in Cooper 2004, unchanged from Hollis et al. 2010).

10.4 BASE UPPER ALTONIAN SUBSTAGE (INFORMAL)

- LO of the planktic foraminifera *Globoconella miozea.* No SSP has been defined.
- No regional calibration. Occurs within lower Chron C5Cn.3n in ODP hole 751 on the Kerguelen Plateau (Berggren et al. 1995a), indicating an age of **16.7 Ma** (Gradstein et

al. 2012) for the base of the upper Altonian (unchanged from Cooper 2004 and Hollis et al. 2010).

10.5 BASE CLIFDENIAN STAGE AND SOUTHLAND SERIES

- LO of the planktic foraminiferal chronospecies *Praeorbulina curva* (= *Globigerinoides (Praeorbulina) glomerosus*) – the horizon where specimens in praeorbuline populations first have 4 or more slit-like apertures at the base of the final chamber embracing 40-70% of the test (Cooper 2004). This event is located within the existing stratotype at Clifden, Southland, which is retained here, although further study is required (Cooper 2004).
- Regional biostratigraphic studies indicate that this event occurs above the 20% dextral threshold associated with the *Globoconella miozea* coiling shift, which occurs within Chron C5Cn.1n at ODP Site 1123 (16.02 Ma, M. Crundwell unpublished data). This suggests that the LO of *Praeorbulina curva* is younger in the New Zealand region than indicated in Berggren et al. (1995a) who placed the event within undifferentiated Chron C5Cn.
- LO of *Praeorbulina curva* and the base of the Clifdenian is provisionally placed slightly above the top of C5Cn.1n (15.974 Ma in Gradstein et al. 2012) and dated as **15.9 Ma** (unchanged from Cooper 2004 and Hollis et al. 2010).

  Note: The current taxonomic concept of *Praeorbulina curva* extends to early praeorbuline morphotypes that Jenkins et al. (1981) included in *Praeorbulina sicana* (Cooper 2004).

10.6 BASE LILLBURNIAN STAGE

- LO of the planktic foraminiferal chronospecies *Orbulina suturalis* – the horizon where adult specimens first have a spherical, almost fully enveloping chamber in the outer whorl, and one or more apertural pores lying outside of the sutural pores (Cooper 2004). The SSP is at Clifden, Southland. A new definition and boundary SSP may be required as planktic foraminifera are sparse in the neritic facies at Clifden (Cooper 2004).
- No regional calibration. The datum corresponds to the global foraminiferal biozone N8/N9 boundary which is reported by Berggren et al. (1995a) to occur in mid-Chron C5Bn.2n, with an inferred age of 15.1 Ma (Gradstein et al. 2012).
- As the age range for this chron has not changed significantly in the past decade, the age of the base of the Lillburnian remains at **15.1 Ma** (unchanged from Cooper 2004 and Hollis et al. 2010).

  Note: Cooper (2004) indicated an informal upper subdivision of the Lillburnian, based on the evolutionary transition from *Orbulina suturalis* to *O. universa*, but Crundwell (2014) has suggested a boundary based on the HO of *Fohsella peripheroronda* s.s. In view of historic differences in recognition of the latter species (see discussion under Waiauan Stage), no division is at present provided.

10.7 BASE WAIAUAN STAGE

- Exact definition of the base of the stage has had a troubled history, and some explanation is required as the choice of datum significantly affects calibration. The stage was originally defined by Finlay & Marwick (1947) on the basis of a molluscan and benthic foraminiferal fauna in the unit stratotype section at Clifden, Southland, the base being marked principally by the LO of *Loxostomum truncatum* and secondarily by the LO of *Cibicides deliquatus*. Fleming et al. (1969) and Hoskins (1978, 1984) further documented and refined this concept. Scott (1991) proposed that the base of the Waiauan be redefined using planktic foraminifera, as this would enhance recognition of the stage in deep-water sediments common in New Zealand strata of this age. After considering various options he suggested the base be defined primarily by the HO of *Fohsella peripheroronda* and secondarily by the HO of *Globorotalia conica*, because these datums were most consistently recognisable and closely approximated the LO of *Loxostomum truncatum* in the unit stratotype. The redefinition was accepted by Cooper (2004), although it was noted that a new SSP might be required. However, later reconsideration of the taxonomic concept of *F. peripheroronda* (Scott pers. comm. 2014) and a review of foraminifera through the Clifden section and other Middle Miocene sites in the Southwest Pacific (M.P. Crundwell, unpublished data) indicates that the HO of *Fohsella peripheroronda* s.s. is well below that adopted by Scott (1991) and the original base of the Waiauan. This conclusion is supported by the age of 13.80 Ma cited for the event by Gradstein et al. (2012). Pending formal reassessment of the definition of the Waiauan, for calibration purposes the HO of *Globoconella conica* is used here as a proxy for the base of the stage.

- The HO of *G. conica* occurs between the base of C5An.2n and the top of C5ABn in ODP hole 1171C on the South Tasman Rise (M. Crundwell, unpublished data). Linear interpolation using the age model of Shevenell & Kennett (2004), recalibrated to the geomagnetic polarity timescale of Gradstein et al. (2012), indicates an age of 13.05 Ma for the HO of *Globoconella conica.* Consequently, the base of the Waiauan is reassigned an age of **13.05 Ma** (12.7 Ma in Cooper 2004, 12.98 Ma in Hollis et al. 2010, 12.7 Ma in Raine et al. 2012).

10.8 BASE UPPER WAIAUAN SUBSTAGE (INFORMAL)

- LO of *Bolboforma subfragoris* s.l., adopted by Crundwell (2014) as a proxy for the base of the upper Waiauan stage and Late Miocene epoch, in deep-water facies. No SSP has been defined.
- Calibrated by Crundwell (2014 and unpublished data) at ODP Site 1123 in an interval of reversed polarity inferred to span Chron C5n.2r and part of Chron C5n.3r, and assigned an interpolated age of **11.67 Ma**.

10.9 BASE TONGAPORUTUAN STAGE AND TARANAKI SERIES

- Base of the Kaiti Coiling Zone – the horizon where populations of the planktic foraminiferal species *Globoconella miotumida* first contain 20% or more of dextral shells (Cooper 2004). As the unit stratotype on the north Taranaki coast is incomplete and lacks the Kaiti coiling zone, a new SSP is needed (Cooper 2004).
- The regional GPTS calibration of this datum is at Chron C5n.2n.015 at ODP 1123 (revised from Crundwell & Nelson 2007). Based on the age range of Chron C5n.2n (9.984 – 11.056 Ma in Gradstein et al. 2012), the base of the Tongaporutuan is assigned an age of **11.04 Ma** (10.92 Ma in Cooper 2004, 11.01 Ma in Hollis et al. 2010, 11.02 Ma in Raine et al. 2012).

Note: Crundwell & Nelson (2007) calibrated two other intervals in the lower Tongaporutuan where populations of *Globoconella miotumida* contain 20% or more of dextral shells: the Mapiri Coiling Zone (MCZ) and the Tukemokihi Coiling Zone (TCZ). These coiling zones have recalibrated ages of 10.68-10.65 Ma and 9.41-9.36 Ma, respectively.

10.10 BASE UPPER TONGAPORUTUAN SUBSTAGE (INFORMAL)

- HO of the planktic foraminiferal species *Globoquadrina dehiscens* (Cooper 2004). This is a well-defined, climatically controlled, regional extinction event, although global extinction occurs later at the Miocene/Pliocene boundary in lower latitudes (Berggren et al. 1995a). Rare specimens also occur in warmer settings in eastern New Zealand up to the Miocene/Pliocene boundary. No SSP has been defined.
- The regional GPTS calibration of the datum is at Chron C4An.43 at ODP Site 1123 (Crundwell & Nelson 2007). Based on the age range of Chron C4An (8.771 - 9.105 Ma in Gradstein et al. 2012), the base of the upper Tongaporutuan is assigned an age of **8.96 Ma** (8.88 Ma in Cooper 2004, unchanged from Hollis et al. 2010).

10.11 BASE KAPITEAN STAGE

- Originally defined as the LO of the molluscan species *Sectipecten wollastoni* at Kapitea Creek, Westland (Finlay & Marwick 1947). However, because this datum occurs in a greensand section in which continuity of deposition is uncertain, and because *S. wollastoni* is restricted to neritic facies, the LO of the planktic foraminiferal species *Globoconella conomiozea* s.s. was provisionally adopted as the primary datum until a new definition and SSP are adopted (Cooper 2004).
- An age of 6.87 Ma was determined for the LO of *Globoconella conomiozea* by interpolation at ODP Site 1123, where it occurs near the base of an unidentified normal polarity interval (Crundwell & Nelson 2007). However, the interpolated age lies within an interval of reversed polarity (Chron C3Ar) and therefore is inconsistent with the actual record at Site 1123. Until a better date is established for the regional appearance of *Globoconella conomiozea* s.s., we place this event, and the base of the Kapitean, near the base of the underlying normal Chron C3Bn (7.140 – 7.212 Ma in Gradstein et al. 2012) and assign an age of **7.2 Ma** (unchanged from Hollis et al. 2010, 6.5 Ma in Cooper 2004).

  Note: Some Waiauan and lower Tongaporutuan populations of *Globoconella miotumida* have four-chambered forms that resemble *G. conomiozea* (Scott et al. 1990, p. 43). These are interpreted as variants of *G. miotumida* that entered the New Zealand sector of the Southwest Pacific from higher latitudes during a period of cooler climatic conditions.

10.12 BASE UPPER KAPITEAN SUBSTAGE (INFORMAL)

- LO of the planktic foraminifera *Globoconella sphericomiozea* s.s. (Cooper 2004). No SSP has been defined.
- Dated at 5.53 Ma (Cooper 2004) by linear interpolation at ODP Site 1123, in an unidentified interval of reversed polarity (Crundwell & Nelson 2007). Interpreted by Roberts et al. (1994) to occur near the middle of Chron C3r at Blind River, an uplifted marine section in Marlborough. Berggren et al. (1995a) report a similar age of 5.6 Ma

for the LO of *Globoconella sphericomiozea* at DSDP Site 588 in the Southwest Pacific. Despite the uncertain chron identification at Site 1123, these lines of evidence support placement of the event in the middle of Chron C3r (5.235-6.033 Ma in Gradstein et al. 2012). On this evidence, the base of the upper Kapitean is assigned an age of **5.6 Ma** (unchanged from Hollis et al. 2010, 5.53 Ma in Cooper 2004).

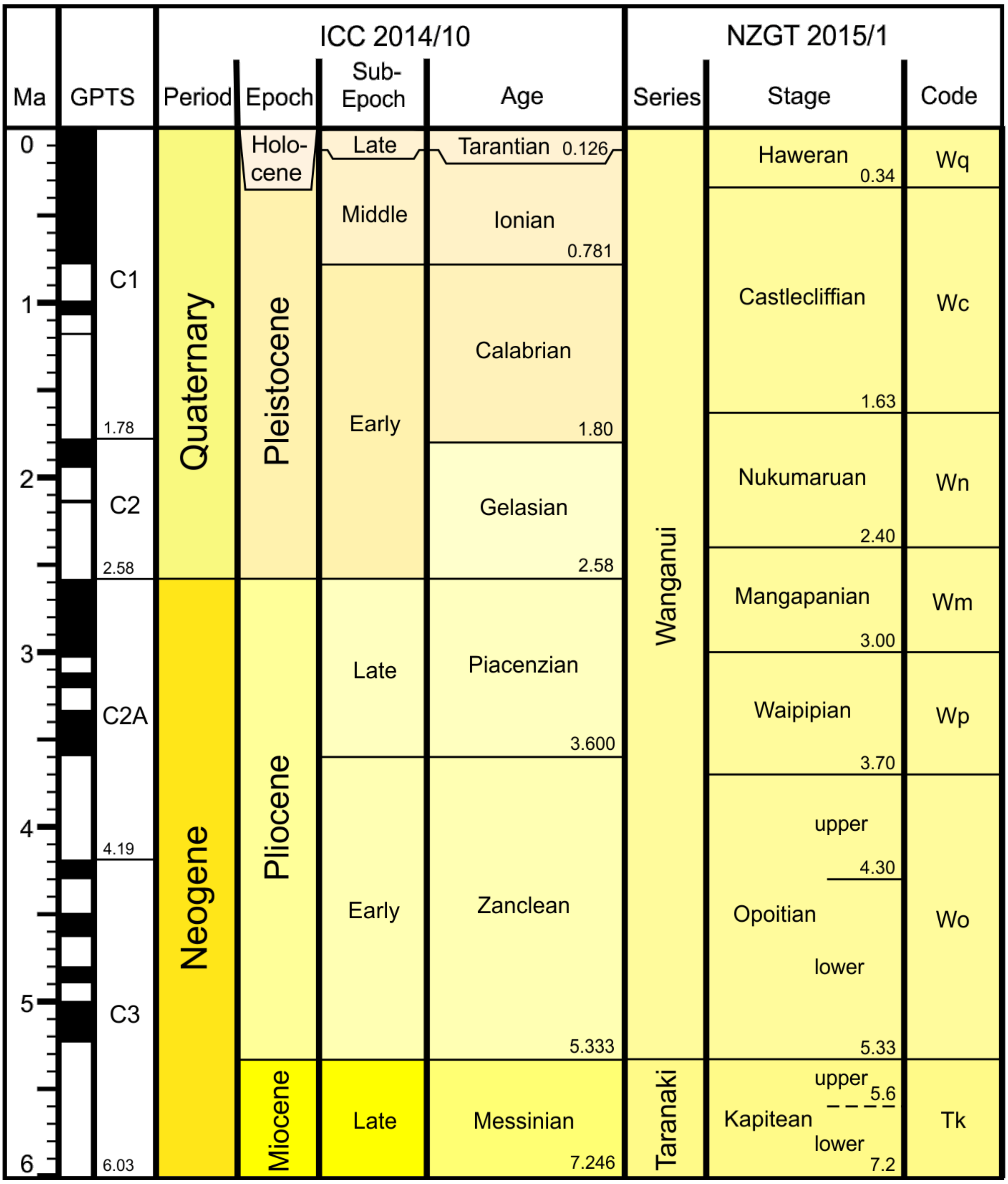

Figure 11 Pliocene to Holocene Timescale. The 2015 calibration of Wanganui Series stages (NZGT 2015/1) with the revised Geomagnetic Polarity Timescale (GPTS, after Gradstein et al. 2012) and Global Geochronological Scale for the Holocene, Pleistocene and Pliocene Epochs, as published in the 2014 International Chronostratigraphic Chart (ICC 2010/10, Cohen et al. 2014).

10.13 BASE OPOITIAN STAGE AND WANGANUI SERIES

- LO of the planktic foraminifera *Globoconella puncticulata* s.s. has been provisionally adopted as the primary datum until a new definition and SSP are adopted; reference sections occur in Hawkes Bay, Wanganui Basin and Westland (Cooper 2004).
- Dowsett (1989) identified the LO of *Globoconella puncticulata* at DSDP Site 590 and used graphic correlation to place it in uppermost Chron C3r (5.235 – 6.033 Ma in Gradstein et al. 2012). This is consistent with records at DSDP Site 284 and ODP Site 1123 (Scott et al. 2007). The event appears to occur later in both lower and higher latitudes (Dowsett 1989; Berggren et al. 1995b; Scott et al. 2007).
- For regional correlation, the mid-latitude timing of this event (upper Chron C3r) is used to date the base of the Opoitian as **5.33 Ma**, which corresponds to the base of the Pliocene (unchanged from Hollis et al. 2010, 5.28 Ma in Cooper 2004).

10.14 BASE UPPER OPOITIAN SUBSTAGE (INFORMAL)

- LO of the planktic foraminifera *Globoconella inflata*, defined as the lowest stratigraphic level where >50% of adult specimens in populations of the anagenetic evolutionary series *Globoconella puncticulata to Globoconella inflata* have <3.5 chambers in the outer whorl (Cooper 2004, Fig. 13.4). No SSP has been defined.
- Provisionally calibrated at ODP Site 1123 in an interval of indeterminate polarity, and assigned an interpolated age of **4.3 Ma** – unchanged from Cooper (2004).

10.15 BASE WAIPIPIAN STAGE

- Beu et al. (1987) and Beu (1995) suggested the boundary be based at the LO of the >110 mm size category of the bivalve *Phialopecten marwickii* in the Mangapoike River section, Hawkes Bay, but this horizon is located at an unconformity and was rejected by Cooper (2004). HO of the calcareous nannofossil *Reticulofenestra pseudoumbilica* has been provisionally adopted as the primary datum until a new definition and SSP are adopted (Cooper 2004).
- The datum occurs in upper Chron C2Ar at ODP Site 1123 (Cooper 2004). This is consistent with the HO of *R. pseudoumbilica* in Gradstein et al. (2012), where a revised age of **3.70 Ma** is provided (3.60 Ma in Cooper 2004 and Hollis et al. 2010).

10.16 BASE MANGAPANIAN STAGE

- LO of the bivalve *Phialopecten thomsoni*, as an evolutionary transition from *Phialopecten marwicki*, at the base of the Mangapani Shellbed, Waitotara Valley, Wanganui Basin. Cooper (2004) adopted this section as the SSP following the recommendation of Beu (2001).
- Correlated to Oxygen Isotope Stage G19 by Carter & Naish (1999) giving the age of **3.00 Ma** (unchanged from Cooper 2004 and Hollis et al. 2010).

  Note: Because *P. thomsoni* is generally only found in shallow-water facies, Crundwell & McDonnell (2014) have suggested an alternative definition based on planktic foraminifera, with SSP at the base of the late Pliocene dextral *Truncorotalia crassaformis* coiling zone in a Rangitikei River section near Mangaweka: if adopted in the future, this would lower the age of the boundary to 3.04 Ma (based on magnetostratigraphic calibration at ODP Site 1123).

10.17 BASE NUKUMARUAN STAGE

- LO of the bivalve *Zygochlamys delicatula* in the basal Hautawa Shellbed, old Hautawa Road section, Wanganui Basin, as recommended by Beu (2001) but not yet formalised. Inferred to be coeval with the LO of the planktic foraminifera *Truncorotalia crassula* and top of the upper dextral coiling zone of *Truncorotalia oceanica* (Cooper 2004).
- Both foraminiferal events occur slightly above the base of Chron C2r at ODP Site 1123, dated at 2.581 Ma by both Berggren et al. (1995a) and Gradstein et al. (2012), giving an interpolated age for the base of the Nukumaruan of **2.40 Ma** (unchanged from Cooper 2004 and Hollis et al. 2010).

10.18 BASE CASTLECLIFFIAN STAGE

- Base of the Ototoka Tephra, Wanganui coastal section. Cooper (2004) adopted this section as the SSP following the recommendation of Beu (2001).
- The base of the stage lies only a short interval above the highest known Nukumaruan macrofossil fauna, which includes several genera and species that became extinct in the New Zealand region at this time. Direct dating of the Ototoka Tephra is however the most useful data for calibration of the base of the stage.
- Fission track dating places the event at ca. **1.63 Ma** (unchanged from Cooper 2004 and Hollis et al. 2010).

10.19 BASE HAWERAN STAGE

- Base of the Rangitawa Tephra, Rangitawa Stream, Rangitikei Valley. Cooper (2004) adopted this section as the SSP following the recommendation of Beu (2001). This definition replaced the earlier concept of the stage (Beu et al. 1987), in which the base was defined as the top of the Putiki Shellbed in a section within Whanganui city.
- The stage boundary was originally thought to be recognisable biostratigraphically by the extinction of *Pecten marwickii*, but this is now believed to be a form of *P. novaezelandiae* and not of value in inter-basinal correlation (Beu 2001, Cooper 2004). Faunal and floral characteristics of the stage are summarised in Cooper (2004): the Rangitawa Tephra fell within Oxygen Isotope Stage 10, just prior to deposition of the Putiki Shellbed.
- Fission track dating and astronomically calibrated age estimates from deep-sea cores (Pillans et al. 1996) place the event at **0.34 Ma** (unchanged from Cooper 2004 and Hollis et al. 2010).

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Table 1 The Global Geochronological Scale, adapted from the International Chronostratigraphic Chart v. 2014/10 (Cohen et al. 2014).

GLOBAL GEOCHRONOLOGICAL SCALE (GGS) 2014

Era	Period	Epoch		Age/Stage	Age of base, Ma
CENOZOIC	Quaternary	Holocene			0.0117
		Pleistocene	Late	Tarantian	0.126
			Middle	Ionian	0.781
			Early	Calabrian	1.80
				Gelasian	2.58
	Neogene	Pliocene	Late	Piacenzian	3.600
			Early	Zanclean	5.333
		Miocene	Late	Messinian	7.246
				Tortonian	11.63
			Middle	Serravallian	13.82
				Langhian	15.97
			Early	Burdigalian	20.44
				Aquitanian	23.03
	Paleogene	Oligocene	Late	Chattian	28.1
			Early	Rupelian	33.9
		Eocene	Late	Priabonian	37.8
			Middle	Bartonian	41.2
				Lutetian	47.8
			Early	Ypresian	56.0
		Paleocene	Late	Thanetian	59.2
				Selandian	61.6
			Early	Danian	66.0
MESOZOIC	Cretaceous	Late		Maastrichtian	72.1
				Campanian	83.6
				Santonian	86.3
				Coniacian	89.8
				Turonian	93.9
				Cenomanian	100.5
		Early		Albian	113.0
				Aptian	125.0
				Barremian	129.4
				Hauterivian	132.9
				Valanginian	139.8
				Berriasian	145.0
	Jurassic	Late		Tithonian	152.1
				Kimmeridgian	157.3
				Oxfordian	163.5
		Middle		Callovian	166.1
				Bathonian	168.3
				Bajocian	170.3
				Aalenian	174.1
		Early		Toarcian	182.7
				Pliensbachian	190.8
				Sinemurian	199.3
				Hettangian	201.3
	Triassic	Late		Rhaetian	208.5
				Norian	227
				Carnian	237
		Middle		Ladinian	242
				Anisian	247.2
		Early		Olenekian	251.2
				Induan	252.17
PALEOZOIC	Permian	Late		Changhsingian	254.14
				Wuchiapingian	259.8
		Middle		Capitanian	265.1
				Wordian	268.8
				Roadian	272.3
		Early		Kungurian	283.5
				Artinskian	290.1
				Sakmarian	295.0
				Asselian	298.9
	Carboniferous	Pennsylvanian		Gzhelian	303.7
				Kasimovian	307.0
				Moscovian	315.2
				Bashkirian	323.2
		Mississippian		Serpukhovian	330.9
				Tournaisian	358.9
	Devonian	Late		Famennian	372.2
				Frasnian	382.7
		Middle		Givetian	387.7
				Eifelian	393.3
		Early		Emsian	407.6
				Pragian	410.8
				Lochkovian	419.2
	Silurian	Pridoli			423.0
		Ludlow		Ludfordian	425.6
				Gorstian	427.4
		Wenlock		Homerian	430.5
				Sheinwoodian	433.4
		Llandovery		Telychian	438.5
				Aeronian	440.8
				Rhuddanian	443.8
	Ordovician	Late		Hirnantian	445.2
				Katian	453.0
				Sandbian	458.4
		Middle		Darriwilian	467.3
				Dapingian	470.0
		Early		Floian	477.7
				Tremadocian	485.4
	Cambrian	Furongian		Age 10	489.5
				Jiangshanian	494
				Paibian	497
		Epoch 3		Guzhangian	500.5
				Drumian	504.5
				Age 5	509
		Epoch 2		Age 4	514
				Age 3	521
		Terreneuvian		Age 2	529
				Fortunian	541.0

Table 2 The 2015 New Zealand Geological Timescale (NZGT 2015/1), showing revised ages for stage boundaries, durations of stages, defining events and boundary stratotypes. For comparison, ages from previous calibrations are also shown: 2004 from the text of Cooper (2004), 2010 from the text of Hollis et al. (2010), and 2012 from the pocket card of Raine et al. (2012).

NEW ZEALAND GEOLOGICAL TIMESCALE 2015/1

NZ Series or International unit	Symbol	Stage	Symbol	Substage (informal)	Symbol	Base age, Ma				Duration, Ma	Lower boundary defining event (and currently used proxy)	Boundary stratotype or (reference section)	SSP?
						2004	2010	2012	2015				
Wanganui Series	W	Haweran	Wq			0.34	0.34	0.34	0.34	0.34	Base of Rangitawa Tephra	Rangitawa Stream, Rangitikei Valley	SSP
		Castlecliffian	Wc			1.63	1.63	1.63	1.63	1.29	Base of Ototoka Tephra	Wanganui coast, Ototoka Stream	SSP
		Nukumaruan	Wn			2.40	2.4	2.4	2.40	0.77	LO *Zygochlamys delicatula*	Base Hautawa Shellbed, Old Hautawa Road, Rangitiki Valley SSP (provisional)	SSP
		Mangapanian	Wm			3.00	3.0	3.0	3.00	0.60	LO *Phialopecten thompsoni*	Base Mangapani Shellbed, Mangapunipuni Stm, Waitotara	SSP
		Waipipian	Wp			3.60	3.6	3.7	3.70	0.70	HO *Reticulofenestra pseudoumbilica* (provisional)		
		Opoitian	Wo	(upper)		(4.25)			4.30	0.60	LO of *Globoconella inflata*		
				(lower)		5.28	5.33	5.3	5.33	1.03	LO *Globoconella puncticulata s.s.*	(Mangapoike River, Hawkes Bay)	
Taranaki Series	T	Kapitean	Tk	(upper)		5.53	5.6		5.6	0.27	LO *Globoconella sphericomiozea* s.s		
				(lower)		6.5	7.2	7.2	7.2	1.60	LO *Sectipecten wollastoni* (LO *Globoconella conomiozea*)		
		Tongaporutuan	Tt	(upper)		8.88	8.96		8.96	1.76	HO *Globoquadrina dehiscens*		
				(lower)		10.92	11.01	11.0	11.04	2.08	Base *Globoconella miotumida* Kaiti Coiling Zone		
Southland Series	S	Waiauan	Sw	(upper)					11.67	0.63	LO *Bolboforma subfragoris* s.l.		
				(lower)		12.7	12.98	12.7	13.05	1.38	HO *Globoconella conica* (provisional)	(Bryce Burn, Waiau Valley, Southland, provisional)	
		Lillburnian	Sl			15.1	15.1	15.1	15.1	2.05	LO *Orbulina suturalis*	(Clifden, Waiau River, Southland)	
		Clifdenian	Sc			15.9	15.9	15.9	15.9	0.8	LO *Praeorbulina curva*	(Clifden, Waiau River, Southland)	
Pareora Series	P	Altonian	Pl	(upper)		16.7	16.7		16.7	0.8	LO *Globoconella miozea*		
				(middle)		18.5	18.2		18.2	1.5	LO *Globoconella zealandica*		
				(lower)		19.0	19.0	18.7	18.7	0.5	LO *Globoconella praescitula*		
		Otaian	Po			21.7	21.7	21.7	21.7	3.0	LO *Ehrenbergina marwicki* lineage	(Bluecliffs, Otaio River, south Canterbury)	
Landon Series	L	Waitakian	Lw			25.2	25.2	25.2	25.2	3.5	LO *Globoquadrina dehiscens*	Trig Z, Otiake, Waitaki Valley	SSP
		Duntroonian	Ld			27.3	27.3	27.3	27.3	2.1	LO *Notorotalia spinosa*	(Landon Creek, Oamaru)	
		Whaingaroan	Lwh	(upper)		30.0	30.1		29.8	2.5	HO *Subbotina angiporoides*		
				(lower)		34.3	34.5	34.6	34.6	4.8	HO *Globigerinatheka index*	Point Elizabeth, Westland	SSP
Arnold Series	A	Runangan	Ar			36.0	36.0	36.4	36.7	2.1	LO *Bolivina pontis*	Sea cliffs, north of Point Elizabeth, Westland	SSP
		Kaiatan	Ak			37.0	38.4	39.1	39.1	2.4	HO *Acarinina primitiva*	Hampden coastal section, Otago	SSP
		Bortonian	Ab			43.0	42.77	42.6	42.6	3.5	LO *Globigerinatheka index*	Hampden coastal section, Otago	SSP
Dannevirke Series	D	Porangan	Dp			46.2	45.3	45.7	45.7	3.1	LO *Elphidium saginatum*	(Te Uri Stream, southern Hawkes Bay)	
		Heretaungan	Dh			49.5	49.3	49.2	48.9	3.2	LO *Elphidium hampdenensis*	(Te Uri Stream, southern Hawkes Bay)	
		Mangaorapan	Dm			53.0	53.3	53.7	52.0	3.1	LO *Morozovella crater*	(Te Uri Stream, southern Hawkes Bay)	
		Waipawan	Dw			55.5	55.8	56.0	56.0	4.0	Onset of PETM carbon isotope excursion	Tawanui Stream, southern Hawkes Bay	SSP
		Teurian	Dt	(upper)		59.7	60.48		61.5	5.5	LO *Fasciculithus tympaniformis*		
				(lower)		65.0	65.5	66.0	66.0	4.5	Base of Boundary clay and iridium anomaly	Flaxbourne River, Marlborough	SSP
Mata Series	M	Haumurian	Mh	Upper	Mhu	74.5	74.5	(79.0)	79.0	13.0	LO *Isabelidinium pellucidum*	Conway River, north Canterbury	SSP
				Lower	Mhl	84.0	83.5	83.6	83.6	4.6	LO *Nelsoniella aceras*	Ben More Stream, Marlborough	SSP
		Piripauan	Mp			86.5	86.5	86.5	86.5	2.9	LO *Inoceramus pacificus*	Ben More Stream, Marlborough	SSP
Raukumara Series	R	Teratan	Rt			89.1	88.6	90.5	90.5	4.0	LO *Inoceramus opetius*	Mangaotane Stream, Raukumara Peninsula	SSP
		Mangaotanean	Rm			92.1	93.0	93.7	93.7	3.2	LO *Cremnoceramus bicorrugatus matamuus*	Mangaotane Stream, Raukumara Peninsula	SSP
		Arowhanan	Ra			95.2	95.2	95.2	95.2	1.5	LO *Magadiceramus? rangatira haroldi*	Mangaotane Stream, Raukumara Peninsula	SSP
Clarence Series	C	Ngaterian	Cn			100.2	100.2	99.5	99.5	4.3	LO *"Inoceramus" tawhanus*	Te Waka Stream, Raukumara Peninsula	SSP
		Motuan	Cm			103.3	103.3	103.3	103.3	3.8	LO *Aucellina euglypha*	Motu Falls section, Raukumara Peninsula	SSP
		Urutawan	Cu			108.4	108.4	108.4	108.4	5.1	LO *Mytiloides ipuanus*	Motu Falls section, Raukumara Peninsula	SSP
Taitai Series	U	Korangan	Uk			117.5	117.5	117.5	117.5	9.1	Presence of *Aucellina* cf. *radiatostriata* assemblage	(Koranga, Raukumara Peninsula)	
		(no stages designated)	Um			145.5	145.5	145.0	145.0	27.5	LO *Ruffordiaspora* (formerly *Cicatricosisporites*) *australiensis*		
Oteke Series	O	Puaroan	Op	Waikatoan	Opw	147.0		(148.2)	148.2	3.2	LO *Belemnopsis aucklandica*	Okahu Stream, Port Waikato	SSP
				Mangaoran	Opm	148.5		150.0	150.0	1.8	LO *Hibolithes arkelli grantmackiei*	Moewaka Stream, Port Waikato	SSP
Kawhia Series	K	Ohauan	Ko	Upper		150.8			152.1	2.1	LO *Belemnopsis trechmanni*	Ohaua Point, Kawhia Harbour (revised)	SSP
				Middle		152.0			152.9	0.8	HO *Retroceramus haasti* (revised)	Lemon Point Road, Kawhia	SSP
				Lower		153.5		154.5	154.5	1.6	LO *Retroceramus haasti*	Whakapirau Road, Kawhia Harbour	SSP
		Heterian	Kh	Upper		155.0			157.3	2.8	LO *Retroceramus subhaasti* (revised)	Heteri Peninsula, Kawhia Harbour	SSP
				Middle		156.0			158.8	1.5	LO *Malayomaorica malayomaorica*	Totara Peninsula, Kawhia Harbour	SSP
				Lower		157.5		164.3	164.3	5.5	LO *Retroceramus galoi*	Totara Peninsula, Kawhia Harbour	SSP
		Temaikan	Kt	Upper		169.0		(169.5)	169.5	5.2	LO *Retroceramus marwicki*	Opuatia Valley, Port Waikato	SSP
				Middle		172.5		(171.0)	171.0	1.5	LO *Retroceramus (Fractoceramus) inconditus*	Opuatia Valley, Port Waikato	SSP
				Lower		175.6		176.0	176.0	5.0	LO *Belemnopsis deborahae*	Opuatia Valley, Port Waikato	SSP
Herangi Series	H	Ururoan	Hu	Upper		183.0		(178.5)	178.5	2.5	LO *Catacoeloceras grangei* (formerly *Dactylioceras*)	near Ururoa Point, Kawhia Harbour	SSP
				Lower		188.0		188.9	188.9	10.4	LO *Pseudaucella marshalli*	Otamaehu Point, near Ururoa Point, Kawhia	SSP
		Aratauran	Ha	Upper		196.5		(199.3)	199.3	10.4	LO *Herangirhynchia arawheroensis*	Ben Bolt, Otapiri Valley, Southland	SSP
				Lower		199.6		201.3	201.3	2.0	LO *Otapiria marshalli*	Otapiri Stm, Hokonui Hills, Southland	SSP
Balfour Series	B	Otapirian	Bo			204.6		209.5	208.5	7.2	LO *Rastelligera diomedea*	Otapiri Stream, Hokonui Hills, Southland	SSP
		Warepan	Bw			212.0		217.0	217.0	8.5	LO *Monotis (Eomonotis) kiritehereensis*	coast S of Kiritehere Stream, SW Auckland	SSP
		Otamitan	Bm			217.0		221.0	221.0	4.0	LO *Manticula problematica*	Otamita Stream, Hokonui Hills, Southland	SSP
		Oretian	Br			227.5		229.0	227.5	6.5	LO *Halobia*	Oreti River, central Southland	SSP
Gore Series	G	Kaihikuan	Gk			238.5		238.0	238.0	10.5	LO *Alipunctifera kaihikuana*	Kaihiku River, near Balclutha, south Otago	SSP
		Etalian	Ge			244.5		245.5	246.0	8.0	LO *Mellarium*	Beaumont Stream, near Ohai, Southland	SSP
		Malakovian	Gm			245.5		246.5	249.0	3.0	(LO *Owenites*)	Coal Creek, near Ohai, Southland	
		Nelsonian	Gn			250.4		251.0	251.5	2.5	LO *Durvilleoceras woodmani*	Iron Pot Point, D'Urville Is.	SSP
D'Urville Series	YD	"Makarewan"	YDm					253.2	253.2	1.7	Lower boundary undefined	(Letham Burn, Wairaki Hills, Southland)	
		"Waiitian"	YDw					254.2	254.2	1.0	Lower boundary undefined	(Wairoa River, Wairoa Gorge, near Nelson)	
		"Puruhauan"	YDp			260.4		259.8	259.8	5.6	Lower boundary undefined	(near Clinton, south Otago)	
Aparima Series	YA	Flettian	YAf			266.5		266.0	266.0	6.2	LO *Echinalosia ovalis*	Letham Burn, Wairaki Hills, Southland	
		Barrettian	YAr			273.0		276.0	276.0	10.0	LO *Spiriferella supplanta*	Letham Burn, Wairaki Hills, Southland	
		Mangapirian	YAm			280.0		285.0	285.0	9.0	LO *Attenuatella altilis*	Wairaki River, southern Takitimu Mtns, Southland	
		Telfordian	YAt			283.0		288.5	288.5	3.5	LO *Plekonella campbelli*	Wairaki River, southern Takitimu Mtns, Southland	
Early Permian (part)		(no stages designated)	Ypt			299.0		298.9	298.9	10.4	NA	NA	
Carboniferous	F					359.2		358.9	358.9	60.0	International units and boundary criteria used	International boundary stratotype sections and points (GSSP's)	
Late Devonian	JU	Famennian	Jfa			374.5		372.2	372.2	13.3			
		Frasnian	Jfr			385.3		382.7	382.7	10.5			
Middle Devonian	JM	Givetian	Jgi			391.8		387.7	387.7	5.0			
		Eifelian	Jei			397.5		393.3	393.3	5.6			
Early Devonian		Emsian	Jzl			407.0		407.6	407.6	14.3			
		Pragian	Jpr			411.2		410.8	410.8	3.2			
		Lochkovian	Jlo			417.2		419.2	419.2	8.4			
Pridoli	Epr					419.7		423.0	423.0	3.8			
Ludlow		Ludfordian	Eld			422.0		425.6	425.6	2.6			
		Gorstian	Ego			423.5		427.4	427.4	1.8			
Wenlock		Homerian	Eho			426.2		430.5	430.5	3.1			
		Sheinwoodian	Esh			428.4		433.4	433.4	2.9			
Llandovery		Telychian	Ete			435.9		438.5	438.5	5.1			
		Aeronian	Eae			439.7		440.8	440.8	2.3			
		Rhuddanian	Erh			443.2		443.8	443.8	3.0			
Late Ordovician		Bolindian	Vbo			449.7		448.4	448.4	4.6	LO *Climacograptus? uncinatus*	(Wangapeka Valley, west Nelson)	
		Eastonian	Vea			456.1		453.0	453.0	4.6	LO *Diplacanthograptus lanceolatus*	(Concordia Gully, east Victoria)	
		Gisbornian	Vgi			460.5		458.4	458.4	5.4	LO *Nemograptus gracilis*	(S ridge of Cobb Valley, west Nelson)	
Middle Ordovician		Darriwilian	Vda			468.1		467.3	467.3	8.9	LO *Undulograptus austrodentatus*	(Slaty Creek, Aorangi Mine)	
		Yapeenian	Vya			468.9		468.3	468.3	1.0	LO *Oncograptus*	(Jimmy Creek, Aorangi Mine, west Nelson)	
		Castlemainain	Vca			472.0		470.0	470.0	1.7	LO *Isograptus victoriae lunatus*	(Bottle Creek, Aorangi Mine, west Nelson)	
Early Ordovician		Chewtonian	Vch			473.9		472.4	472.4	2.4	LO *Didymograptellus protobifidus*	(Anthill Creek, Aorangi Mine, west Nelson)	
		Bendigonian	Vbe			476.8		476.0	476.0	3.6	LO *Pendeograptus fruticosus*	(Anthill Creek, Aorangi Mine, west Nelson)	
		Lancefieldian	Vla			488.7		484.3	484.3	8.3	LO *Rhabdinopora scitulum*	Stauro Gully, Victoria	SSP
		Warendan	Vwa			490.0		485.4	485.4	1.1	LO *Cordylodus lindstromi*	(Ridge north of Mount Patriarch, NW Nelson)	
Furongian		Datsonian	Xda			491.5		486.8	486.8	1.4	LO *Cordylodus proavus*	Black Mountain, western Queensland	
		Payntonian	Xpa			494		489.5	489.5	2.7	LO *Sinosaukia impages*	Black Mountain, western Queensland	
		Iverian	Xiv			498.5		494.0	494.0	4.5	LO *Irvingella tropica*	Black Mountain, western Queensland	
		Idamean	Xid			501		497.0	497.0	3.0	LO *Glyptagnostus reticulatus*	No boundary stratotypes or reference sections nominated	
		Mindyallan	Xmi			503		499.0	499.0	2.0	LO *Erediaspis eretes*		
Cambrian Epochs 2-3		Boomerangian	Xbo			504		500.5	500.5	1.5	LO *Ptychagnostus cassis*		
		Undillan	Xun			505		503.0	503.0	2.5	LO *Ptychagnostus punctuosus*		
		Floran	Xfl			507		504.5	504.5	1.5	LO *Ptychagnostus atavus*		
		Templetonian	Xle					508.0	508.0	3.5	LO *Pentagnostus anabarensis*		
		Ordian	Xor			513.0		511.5	511.5	3.5	(*Redlichia chinensis* fauna)		
Cambrian Epochs 1-2	XL					543.0		541.0	541.0	29.5	(Not known in New Zealand)	(Not known in New Zealand)	

NA = not applicable LO = Lowest occurrence HO = highest occurrence