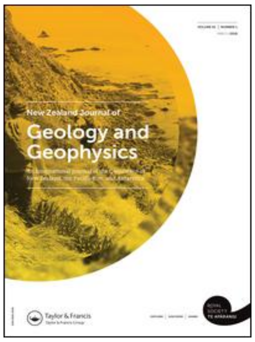

Taylor & Francis
Taylor & Francis Group

New Zealand Journal of Geology and Geophysics

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tnzg20

The New Zealand Fossil Record File: a unique database of biological history

Christopher D. Clowes , James S. Crampton , Kyle J. Bland , Katie S. Collins , Joseph G. Prebble , J. Ian Raine , Dominic P. Strogen , Marianna G. Terezow & Tom Womack

NEW ZEALAND JOURNAL OF GEOLOGY AND GEOPHYSICS
https://doi.org/10.1080/00288306.2020.1799827

Taylor & Francis
Taylor & Francis Group

REVIEW ARTICLE

The New Zealand Fossil Record File: a unique database of biological history

Christopher D. Clowes[a], James S. Crampton[b], Kyle J. Bland [a], Katie S. Collins [c], Joseph G. Prebble[a], J. Ian Raine[a], Dominic P. Strogen [a], Marianna G. Terezow[a] and Tom Womack[b]

[a]GNS Science, Lower Hutt, New Zealand; [b]School of Geography, Environment and Earth Sciences, Victoria University of Wellington, Wellington, New Zealand; [c]The Natural History Museum, London, UK

ABSTRACT
The New Zealand Fossil Record File, an essentially complete compilation of New Zealand's known fossil record, with additional records from parts of Antarctica, SW Pacific, and elsewhere, is, to the best of our knowledge, unique. It has developed collaboratively, with contributions from university, government, industry, and avocational paleontologists and geologists. The distinctive Fossil Record Number has become an icon of New Zealand geological literature since inception of the original paper-based archive in the 1940s. Subsequently, the file has been digitised and currently holds >100,000 locality records and >1,000,000 individual taxonomic identifications spanning numerous plant and animal phyla. These numbers are continually growing. The database contains contextual information on geographic location, collection, stratigraphy and lithology of the fossil localities as well as taxonomic analyses that retain original identifications yet accommodate re-assignments. The data have been widely applied, initially for mapping, establishing age, depositional environment, etc., and more recently including in quantitative biostratigraphy, assessing completeness of the fossil record, understanding biodiversity history, extinction risk assessments, and climate analysis. In this paper, we provide a brief overview of the history of the Fossil Record File, indicate the general nature of the data it contains, and showcase a number of innovative applications of this most valuable resource.

ARTICLE HISTORY
Received 30 April 2020
Accepted 20 July 2020

HANDLING EDITOR
Erica Crouch

KEYWORDS
Biostratigraphy; fossils; FRED; FRF; Nationally Significant Collections and Databases; New Zealand Fossil Record File; paleontological database; taxonomy; world wide web

Introduction

The 'fossil record' is the sum of the physical, sedimentary and chemical records of life on Earth. Fossils provide key data on evolution, extinction including mass extinction, past environmental change including climate change, development of the Earth system, geochemical cycling, and plate tectonics. The geological time scale, which is used to order and date geological events and to calculate rates of geological processes, is predominantly based on correlation by means of fossils. The time scale is fundamental to the discovery of geological resources and the quantification of geological hazards. There is little geology or geophysics that fossils do not underpin in some way. They provide unique and, in many cases, surprising data on the ancestors and development of the living biota; for New Zealand/Aotearoa, they are the whakapapa of our celebrated flora and fauna. The fossil record gives a historical context for research into present-day and future climate change, and it contains critical information about thresholds in life-support mechanisms of the Earth system and biosphere; this information can guide our responses to anthropogenic climate and environmental change.

New Zealand has an extremely rich fossil record, especially for the Late Cretaceous to Recent. This record is internationally important because it provides the only readily accessible data source for a large sector of the southwest Pacific: a significant fraction of the Earth's surface. As researchers seek to understand and model globally connected Earth systems, data from comparatively under-studied parts of the Southern Hemisphere, including New Zealand, are becoming increasingly important. Geologists in New Zealand are fortunate that, relatively early in the development of the discipline here, paleontological information was compiled into a national data archive that has become the New Zealand Fossil Record File (FRF). Broadly similar databases exist elsewhere and some, such as the Paleobiology Database, are 'larger' (hold more records) in absolute terms. Where the FRF is uniquely different, however, is its comprehensive coverage of an entire region.

Here, we give a brief introduction to this resource that is, to the best of our knowledge, unique in the world, indicating the general nature of the data it contains and showcasing a number of innovative applications.

Historical development

Methodical published research into New Zealand's paleontological archive began with the visit of Ferdinand von Hochstetter in 1858–59, and publication of

CONTACT Christopher D. Clowes c.clowes@gns.cri.nz

the geological memoirs of the 'Novara' Expedition in 1864. Arguably, however, Hochstetter's most enduring legacy may lie in having persuaded several New Zealand provincial governments to establish geological surveys. Eventually, in 1865, these were disbanded and replaced by a new national organisation, the New Zealand Geological Survey (NZGS) and Colonial Museum.

NZGS paleontologists established and maintained various catalogues and specimen inventories for their own use from the earliest days; some of these original card catalogues are still in existence and fossil collections dating back to the late 1800s are now incorporated into the National Paleontological Collection. In 1946, however, NZGS adopted a common format across the whole organisation – the Fossil Record Form – to systematically record details of fossil collections and taxonomic identifications. Fleming (1958, p. 27) claims that this initiative was motivated largely by Harold Finlay's biostratigraphic work, although Nathan (2005, pp. 88–91; also Gage 1982, p. 46) ascribes the central role to Harold Wellman, not least for the decision to organise the system geographically, by map sheet.

Each of these Fossil Record Forms was assigned a unique identifier consisting of two parts, a map sheet reference and a serial number, and the distinctive formulation of this Fossil Record Number (FRN) has now become an icon of New Zealand paleontological and broader geological literature. Similar map + serial number schemes have been adopted elsewhere; the registration of New Zealand archaeological sites is one example. The FRN was allocated by an administrator with responsibility for the geographic area from which the collection was made. At least as early as 1958, administration of the file and storage of the forms was distributed among different institutions (Fleming 1958, p. 29). The first FRN was allocated in 1947 (Sudlow and Edwards 1982) and with it began the first recognisable version of the New Zealand Fossil Record File.

The original Fossil Record Form was a single sheet of paper designed to capture the key data concerning a specific fossil collection (or observation) from a specific location. (Early examples are illustrated by Gage 1982, p. 47; Nathan 2005, p. 90.) Extensive archives of paper forms still exist, although digital data capture direct from collectors' field books has almost completely replaced their use today.

The history of the FRF has been punctuated by multiple migrations to different media. Most uses of FRF data, especially today's sophisticated, large-volume data analyses, would be impossible if the data were not available in digital form. Transcription of the paper-based forms to the first in a series of digital electronic platforms commenced in 1970 (see Raine 1992), notably championed by NZGS staff Guyon Warren, George Scott, and Ian Raine. Presently, the database is provided by an Oracle platform hosted by GNS Science (the present successor organisation of NZGS), and the user interface is an application written to support several popular web browsers. This application is known as 'FRED', an acronym for Fossil Record Electronic Database, and is accessible at fred.org.nz.

Another significant event in the history of the FRF was the conversion from an imperial to metric mapping projection. During the 1970s, the underpinning map sheet series was migrated from a long-standing imperial map series, NZMS1, to the then-new metric 1:50,000 NZMS260 national topographic map series. Although the same conceptual pattern of sheet reference/serial number was maintained, duplicate serial numbers from adjacent NZMS1 sheets now occurred within a single NZMS260 sheet, requiring a complicated renumbering algorithm. The NZMS1 master files were closed in 1975. The NZMS260 map series has, itself, since been superseded by the Transverse Mercator-based Topo50 series but the ubiquity and versatility of digital mapping has meant further renumbering of the FRF is unnecessary.

The New Zealand Fossil Record File has been, and continues to be, developed collaboratively by university, government research institute, industry, and avocational paleontologists and geologists (e.g. Schiermeier 2003). Due in no small part to this diverse cooperative network of contributors, the FRF has grown over time to become an essentially complete compilation of New Zealand's known fossil record. Additional records from wider Zealandia (Mortimer et al. 2017), parts of Antarctica and the southwest Pacific are also useful, but presently are insufficiently comprehensive to support the same kinds of studies as can be applied to mainland New Zealand.

Data description

Modelled on the format of the paper forms, the FRED application aggregates individual data fields (mandatory fields underlined) into contextual groups concerned with:

- geographical locality (including <u>grid references</u> and a <u>text description</u> of the geographical locality, depth interval in the case of drill holes; grid references can be entered in a variety of formats and resolutions, and are automatically converted to a standard, currently WGS84 [World Geodetic System 1984]);
- collection (<u>collectors' names</u>, <u>collection date</u>, fossils seen but not collected, whether the fossils are in situ or not, where the collected material was sent);
- stratigraphy (lithostratigraphic name, known and inferred age/stage limits, relationships to other units, attitude, map or column references);

- lithology (grain size, stratification, weathering, hardness, colour and inferred environment, among others);

and what we will here call the 'taxonomic analysis', which is characterised by the person making the fossil identifications and the date when they did so. This is an important concept because, commonly, several different people will examine the same collection, each studying and identifying different kinds of fossil groups, often at different times. Each of these separate examinations will result in a separate 'taxonomic analysis' for the same collection. Moreover, the same or a different person might re-examine any of the fossil groups and revise some or all of the identifications at a later date. If this happens, the original taxonomic analysis is retained and a new one is simply appended to the overall record; once recorded, no information is deleted.

Age data are recorded at several places depending upon the context, including initial field assessment, associated with each taxonomic analysis, and by means of an explicit age adoption step. An automated best guess on the basis of all data recorded to date is also available. The age model used is the most recent version of the New Zealand Geological Timescale (currently Raine et al. 2015). Obsolete time units are retained for historical accuracy, but calibrations are updated so that records expressed in obsolete terms will still appear correctly in searches.

Detailed descriptions of the data format expected for each individual field, together with usage instructions, are provided in an on-line manual available directly from the FRED application home page, fred.org.nz.

Whereas the great majority of data in the FRF derives from the New Zealand mainland (Figure 1) and some traditional areas of responsibility, such as the Ross Sea and adjacent areas of Antarctica, extensions to the map sheet component of the numbering system allow it to accept data from anywhere in the world, and some international localities are indeed represented in the FRF. New Caledonia, several Pacific Islands, and a few seafloor drill hole collections are particularly well-represented.

There are also facilities to upload field or other photographs, sketches, and other imagery.

Metrics

At the time of writing, the FRF holds >100,000 locality records, >100,000 paleontological analyses, and >1,000,000 individual taxonomic identifications. These numbers are increasing by ~60 new localities and ~45 new paleontological analyses, on average, each month.

The paleontological data are irregularly distributed across the different taxonomic groups, but at least the following taxonomic groups are very well-represented: foraminifera, molluscs, miospores, dinoflagellates, calcareous nannofossils, and brachiopods (Figures 2–3).

The most prodigious contributors comprise a mix of active contemporary researchers, as well as familiar names from the past, such as Norcott Hornibrook, George Scott, Harold Finlay, Jack Marwick and Charles Fleming.

Although the application does presently log some user activity, it does not capture comprehensive usage statistics; web site analytics indicate something in the order of 6000 to 7000 data searches are requested each year, but more granular statistics are unavailable. Citations in articles and professional papers are monitored informally.

Governance and administration

The Fossil Record File is one of 24 'Nationally Significant Collections and Databases' recognised by the New Zealand Government, and directly supported through the Strategic Science Investment Fund.

GNS Science is the recognised custodian of the file, but, importantly, it is governed jointly with the Geoscience Society of New Zealand (GSNZ). A memorandum of understanding between these two bodies explicitly recognises a wider range of stakeholders, including 'individuals, amateur enthusiasts, students, scientists and organisations in the public and private sectors.' The aims of the partnership recorded in the memorandum of understanding are to:

(1) provide a central location where all data relevant to locality, taxonomy, age and the paleoenvironmental interpretation of Zealandia's fossil record (Data) can be stored;
(2) encourage stakeholders to lodge their Data and make their Data available; and
(3) provide fast and flexible ways to access the Data.

In broad terms, the division of responsibilities is for GNS Science to provide the technology platform and associated maintenance; for GSNZ to promote use of the system and to advocate on behalf of the user community; and for the data originators to share their data with their peers in the paleontological community. (There is an expectation of appropriate recognition for both the originator of the data and for the FRF itself; guidelines are posted onfred.org.nz.)

FRED

FRED is the on-line web application that provides access to FRF data.

Some functions, such as access to the user manual, are available to anybody but, for most purposes, users are required to register for an account. However,

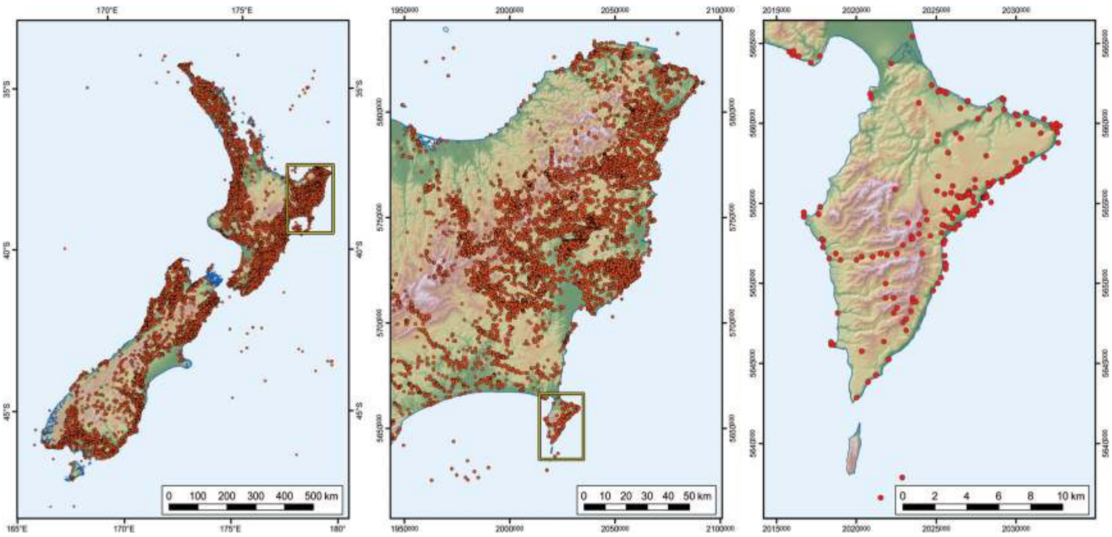

Figure 1. Example maps of New Zealand mainland (>73,000 localities), Raukumara Peninsula (>13,000 localities), and detail of Mahia Peninsula (212 localities), to illustrate the density and distribution of fossil localities recorded in the Fossil Record File.

registration is free and there are no restrictions on who can apply. Amateurs, academics, students and industry are all welcome and active members of the user community.

By default, all registered users are authorised to search for and download data ('read' permission; Figure 4). Additional rights are required to add new data ('write' permission) but, again, the additional permission is free and there are few restrictions on who can apply.

In some cases, such as observations of taxa already known to the system from an existing collection, checking of newly entered data is carried out automatically and the new data are accepted immediately. For the most part, however, new locality and taxonomic data are sent to curators for validation. The FRF curators are drawn from the experts available in New Zealand universities and GNS Science. A separate administrative permission, held by only a small number of administrators, is required to change existing records, update the system reference tables, and change user permissions.

User activity is logged by the application. In principle these logs could provide a useful guide to future enhancements but, at the time of writing, their only use is to diagnose faults in the code ('bugs').

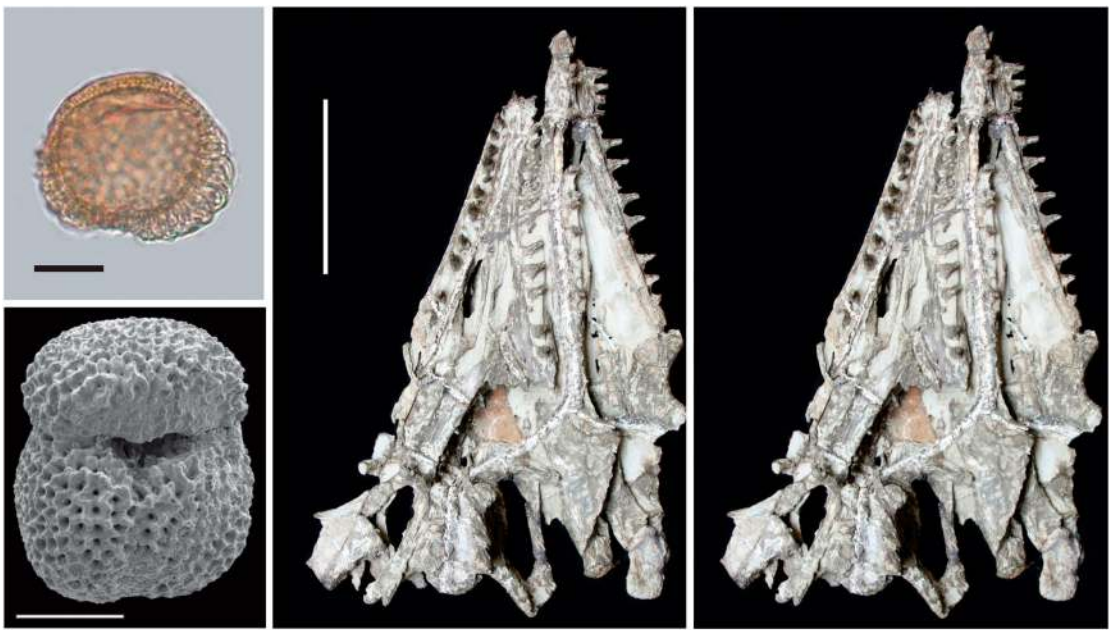

Figure 2. Left – Two of the most common fossil taxa recorded in the Fossil Record File, a rimu pollen grain, *Dacrydium cupressinum* (top; scale bar = 20 µm) and the foraminifer *Globoquadrina dehiscens* (bottom; scale bar = 200 µm). Right (stereo pair) – One of the rarest taxa recorded, the mosasaur *Rikisaurus tehoensis* (V19/f0068; scale bar = 200 mm). The microfossils have each been recorded more than 5000 times; the mosasaur only once.

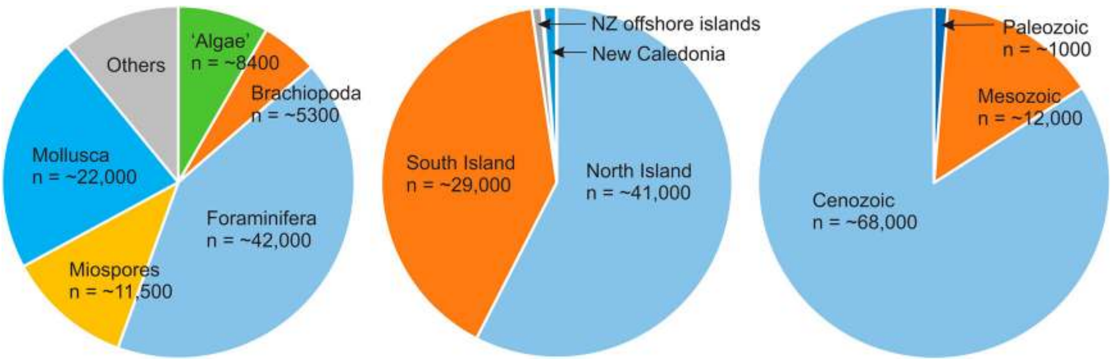

Figure 3. Relative contributions of records within the Fossil Record File based on sample counts at June 2020. If a category could not be assigned (e.g. a record with no age determination) the record was not counted. **A.** By taxonomic group. Clockwise from top: 'Algae' (including dinoflagellates and nannofossils), brachiopods, foraminifera, miospores, molluscs, others. **B.** By geography. Clockwise from top: North Island, South Island, NZ offshore islands, New Caledonia (others too small to indicate). **C.** By age. Clockwise from top: Paleozoic, Mesozoic, Cenozoic.

Applications

The 'ordinary' day-to-day applications of FRF data – guiding future field work, searching out specimens for taxonomic studies, and so on – are built around the various search functions. Data can be located using any combination of geographic, stratigraphic and taxonomic criteria, although only a single tier search is currently available. (A 'search within results' function is on the drawing board but not yet in development.)

On a larger scale, FRF data has informed geological mapping projects ranging from those of Wellman and his contemporaries in the 1940s, through to the nation-wide 1996–2011 QMAP geological mapping campaign (Rattenbury and Isaac 2012), either directly or indirectly via the New Zealand Stratigraphic Lexicon and the New Zealand Geological Time Scale.

However, research applications are not always foreseen ahead of time but arise a posteriori as a consequence of having a resource in the first place; much of the real, mostly untapped potential of the FRF lies in 'big data' analysis. Because the FRF provides an essentially complete catalogue of the known fossil record of New Zealand, with associated information on the stratigraphical and sedimentological context of fossil occurrences, it therefore provides a globally

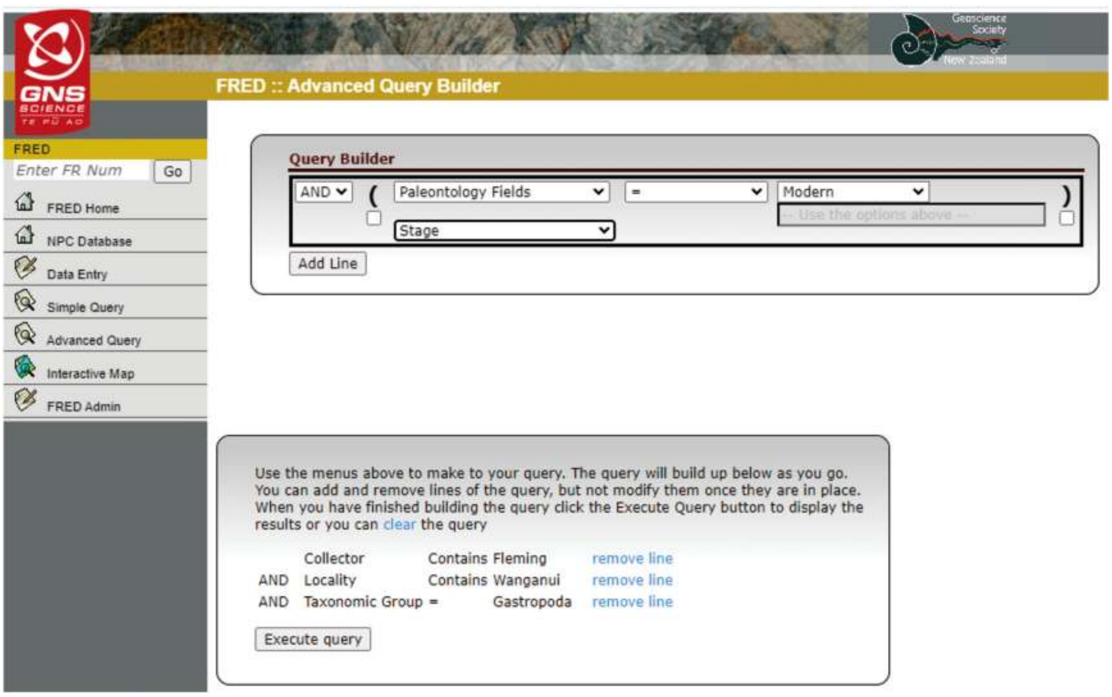

Figure 4. Several different query facilities are provided by the FRED interface into the FRF, the most comprehensive of which is the 'Advanced Query'. The figure depicts a partially populated Advanced Query search screen. Search fields are grouped into various categories (locality, stratigraphy, taxonomic, etc.) and a selection of operators (equals, contains, numeric inequalities, etc.) to allow a series of Boolean statements to be constructed. Full instructions are provided in the on-line user manual.

unique resource that can be used to investigate complex interrelationships between the geological and fossil records, changes in environment and biodiversity over time, and aspects of macroevolution.

Below we present five examples of individual studies or ongoing research 'themes' where analysis of FRF data has provided fundamental research advancements.

Case Study 1: high resolution quantitative biostratigraphy, correlation, and timelines

The FRF provides huge scope for the interrogation and syntheses of large amounts of biostratigraphic data in order to produce high-resolution, quantitative biostratigraphic schemes and correlations that can be used for basin analysis and many aspects of geohistorical inference. In particular, quantitative biostratigraphy enables the discipline to move beyond the relatively low resolution of formal biostratigraphic zonations, and to derive more-or-less continuous timelines of species first- and last-occurrences (e.g. Cody et al. 2008). In many cases, biostratigraphic resolution is increased by one to two orders-of-magnitude over traditional zonations. An early and widely cited study of this sort used FRF data from eight petroleum exploration wells in Taranaki Basin to test two key quantitative biostratigraphic methods, Constrained Optimization (CONOP) and Ranking and Scaling (RASC), and to produce highly resolved age-depth interpretations and correlations across the basin (Cooper et al. 2001). Results from this study, for example, constrained the timing and duration of known and newly identified unconformities in Taranaki Basin. Quantitative biostratigraphic methods, in particular CONOP, subsequently have employed FRF data for several industry-focussed studies of New Zealand sedimentary basins (e.g. Crampton et al. 2012; Raine and Schiøler 2012). These methods continue to evolve, with the explicit integration of geophysical, chemo- and lithostratigraphic, and most recently, cyclostratigraphic data (e.g. Sadler et al. 2014, and references therein).

Using data from elsewhere in the world, quantitative biostratigraphic analyses are being used increasingly to refine the international geological time scale (e.g. Cooper et al. 2012; Sadler et al. 2009) and to interpret biological and evolutionary history in the context of global change (e.g. Jaramillo et al. 2006; Crampton et al. 2016). To date, FRF data have not been used in this way, although the database offers almost unparalleled opportunity for regional-scale, quantitative biostratigraphic studies of this sort (for a recent, global example of this sort of application, see Fan et al. 2020).

Case Study 2: nature of the fossil record and biodiversity history

A suite of papers have used data on New Zealand Cenozoic molluscs retrieved from the FRF to quantify widely discussed but poorly constrained biases in the fossil record related to the volume of rock available for sampling (Crampton et al. 2003; Hendy 2009), the second-order sequence stratigraphic context of sampled formations (Crampton, Foote, Beu, Cooper, et al. 2006), body size (Cooper et al. 2006), and preferential loss of aragonitic shells that are mineralogically less stable than calcitic shells (Foote et al. 2015). Concurrently, and using a variety of approaches to mitigate the biases noted above, companion papers have used the same data to answer paleobiological questions. These include studies of Cenozoic mollusc biodiversity (Crampton, Foote, Beu, Maxwell 2006), to determine how species expand over time to fill their geographic ranges and then contract prior to extinction (Foote et al. 2007), and to identify key ecological determinants of species longevity (Crampton et al. 2010).

Currently, these lines of research are being extended to look in more detail at controls on marine biodiversity, a question that is central to paleobiology and highly germane considering the current biodiversity crisis (Urban 2015; Ceballos et al. 2017). Historically, such studies have focused on diversity at specific sites or at the largest scale (global or continental). Evidence suggests, however, that most diversity resides at intermediate scales, represented by species turnover from site to site, broadly referred to as beta diversity (Holland 2010; White et al. 2010). This new research focuses on the relationship between the different partitions of diversity, particularly beta diversity, and the spatial structuring of the environment, to understand how processes of diversification interact with habitat change across spatial and temporal scales. New Zealand provides a model system for understanding patterns of diversity spatially and temporally due to its exceptional Cenozoic sedimentary stratigraphic record and shallow marine fossil record that extend to the Recent, regarded as the most complete in the Southern Hemisphere (Crampton, Foote, Beu, Maxwell et al. 2006). This new research is facilitated by FRF data and supplemented with collections obtained through fieldwork in exemplary Pliocene–Pleistocene sections in Hawke's Bay and Whanganui (e.g. Bland et al. 2013; Buckeridge et al. 2018; Womack et al. 2018). Because FRF taxonomic identifications have been generated by comparatively few, mostly closely collaborating paleontologists, the data are characterised by relative taxonomic stability and consistency. For this reason, FRF data can be analysed at the species level and at the regional scale (New Zealand-wide), providing levels of detail and resolution that are commonly not available in paleontological studies.

Case Study 3: extinction risk assessments of marine invertebrate species

Collins et al. (2018) provides an extinction risk assessment metric intended for wider use on marine invertebrate species, by combining paleontological data, in the form of extinction rates calculated from the fossil record, with two known correlates of risk in the modern day: geographical range size and realised thermal niche (the range of temperatures that the organism is known to encounter throughout the year across the breadth of its geographic range). They test the performance of this metric by using survivorship analyses of Pliocene bivalve faunas from California and New Zealand, the latter derived from an analysis of FRF data. The metric is then used to identify present-day hotspots of extinction vulnerability (regions in which many species are at high risk) for extant shallow-marine Bivalvia. Areas of the ocean where concentrations of bivalve species with higher scores overlap with high levels of climatic or anthropogenic stressors are considered to be potentially vulnerable. Despite differences from a previous study (Finnegan et al. 2015) in terms of methodology and data, New Zealand and the Caribbean were identified by both studies as two of the strongest hotspots in terms of proportion of the biota at risk. FRF data were crucial to the study of Collins et al. (2018) and the development of their extinction risk metric; other, global, databases of paleontological data were queried to try and locate other suitable faunas for testing, and none was found to be complete enough for use. Furthermore, the stability of mollusc taxonomy in the FRF, where most determinations have been done by only a handful of experts who often worked closely with each other, improved ease of use of the data without need for extensive cross-checking of identifications: species concepts are relatively stable in the FRF in comparison to some data compilations for other regions.

Case Study 4: terrestrial climate from bioclimatic analysis

Prebble et al. (2017) proposes a reconstruction of terrestrial temperature and precipitation for the New Zealand landmass over the past ~30 million years. The reconstruction was produced using pollen data from >2000 samples lodged in the FRF, interpreted using the modern climate preferences of nearest living relatives (Greenwood et al. 2005; Raine et al. 2011; Reichgelt et al. 2013). Their model reveals a warming trend through the late Oligocene to early Miocene, peak warmth in the middle Miocene, and stepwise cooling through the late Neogene. Whereas the regional signal in their reconstruction will be influenced by a ~5°–10° latitude northward tectonic drift (Cande and Stock 2004; Van Hinsbergen et al. 2015), as well as an increase in high altitude biomes due to late Neogene and Pliocene uplift of the Southern Alps (Cox and Sutherland 2007), the pattern mimics inferred changes in global ice extent, which suggests that global drivers played a major role in determining local vegetation. Importantly, seasonal temperature estimates indicate low seasonality during the middle Miocene, and that subsequent Neogene cooling was largely due to cooler winters. This work extends earlier studies (Mildenhall and Pocknall 1984; Pocknall 1989; Beu 1990; Pocknall 1990; Hornibrook 1992) and provides more robust, repeatable and clearly documented evidence by its use of an open access database.

Case Study 5: seismic interpretation and paleogeographic reconstructions

Understanding sub-surface stratigraphy and paleoenvironments of strata is of fundamental importance to reconstructing basin histories and for commercial applications, chief among which is petroleum exploration. Seismic reflection data are a primary means of mapping subsurface geology. However, accurate seismic interpretations cannot be confirmed without ties to drill holes to provide age and lithostratigraphic control points. In New Zealand, these control points have almost invariably been achieved through detailed biostratigraphic analysis of fossil material recovered from petroleum exploration wells and lodged in the FRF. Because data within the FRF are digital, and have associated grid-references, they can be readily loaded into Geographic Information Systems and other computer-based mapping packages. Several detailed studies of the late Paleogene and Neogene evolution of Taranaki Basin have utilised FRF data to constrain seismic horizons, lithostratigraphic and chronostratigraphic horizons between drill holes, and paleoenvironments through time (e.g. Strogen et al. 2014, 2019; Bull et al. 2019). Data in the FRF also underpin detailed paleogeographic maps of New Zealand and its offshore realm, providing critical information on age, water depths, oceanicity, and the composition of vegetated areas on-land. A summary of the latest Neogene paleogeographic evolution of central New Zealand is given by Trewick and Bland (2012). Extensive use of FRF data from petroleum exploration wells was made in developing the regional-scale suites of paleogeographic maps and seismic interpretations within the Atlas of Petroleum Prospectivity (e.g. Arnot et al. 2016, 2018; Sahoo et al. 2017; https://data.gns.cri.nz/PBE/index.html?menu=APP).

Recent initiatives and future development

Work to improve the utility of the FRF proceeds on several fronts, which may be informally grouped into Data and Functional initiatives. The former refers to ongoing efforts to capture new data and improve the quality of existing data, ranging from trivial spelling corrections to tracking down and entering overlooked paper forms in desk drawers or behind filing cabinets or, in some cases, from university theses and published works that were never submitted to the FRF originally.

Functional improvements have included implementation of a 'consensus age' concept, automatically constructed from all data available for each record according to a set of business rules. An improved facility to support uploading data from spreadsheets is currently in development.

Possible future initiatives include taxonomic synonymies, more sophisticated data retrieval functions to facilitate the kind of data analysis exemplified by the case studies described above, and improved mapping functions.

Conclusion

The Fossil Record File has been an invaluable resource for geologists and paleontologists in New Zealand since its inception, providing a central data repository for the fruits of both geological mapping and paleontological research. Providing easy access to the aggregated data in turn has fostered and inspired further work, leading to a synergy between those two disciplines. As the case studies show, the usefulness and relevance of the FRF continues to this day. We hope that by showcasing some of the work people have done using FRF data, we will encourage its ongoing use.

Collaborative participation by generations of university, government research institute, industry, and avocational paleontologists is the unique strength of the FRF. It is greatly to be hoped that present and future generations of scientists continue this tradition of selflessly sharing their data, and continue to support our amazing, unique, collaborative database.

Acknowledgements

First and foremost, the authors thank the hundreds of geologists and paleontologists who have generously contributed data to the Fossil Record File and its forerunners, for more than 150 years, simply for the common good and furtherance of science. CDC additionally thanks Mark Rattenbury for suggesting this paper, Simon Nathan for helpful discussion, and Martin Crundwell for the SEM image of *Globoquadrina dehiscens*. The authors are very grateful to Neville Hudson, Mark Uhen, one anonymous reviewer and the Editor, Erica Crouch, for suggesting improvements to the manuscript.

Disclosure statement

No potential conflict of interest was reported by the author (s).

Funding

The New Zealand Fossil Record File is funded by Strategic Science Investment Funding provided by the New Zealand Government, Ministry of Business, Innovation and Employment (MBIE), to GNS Science as part of the Nationally Significant Collections and Databases programme.

Data availability statement

Data sharing is not applicable to this article as no new data were created or analysed in this study.

ORCID

Kyle J. Bland http://orcid.org/0000-0002-9038-0208
Katie S. Collins http://orcid.org/0000-0002-3379-4201
Dominic P. Strogen http://orcid.org/0000-0002-1744-1289

References

Arnot MJ, Bland KJ, Boyes AF, Bull S, Funnel RH, Griffin AG, Hill MG, Kroeger KF, Lukovic B, Scadden PG, Seebeck HC, Strogen DP, Town CC, Viskovic GPD (compilers). 2016. Atlas of petroleum prospectivity, Northwest Province: ArcGIS geodatabase and technical report. GNS Science Data Series 23b. 5 ArcGIS projects, 1 ArcGIS geodatabase, and technical report.

Arnot MJ, Lawrence MJF, Viskovic GPD, Zhu H, Bland KJ, Strogen DP, Schuurmans R (compilers). 2018. Atlas of petroleum prospectivity, Southwest Province (West Coast, Fiordland, and western Southland basins). GNS Science Data Series 23e. 1 ArcGIS geodatabase, 3 ArcGIS projects, 23 illustrated seismic transects, and technical report.

Beu AG. 1990. Molluscan generic diversity of New Zealand Neogene stages: extinction and biostratigraphic events. Palaeogeography, Palaeoclimatology, Palaeoecology. 77:279–288.

Bland KJ, Hendy AJW, Kamp PJJ, Nelson CS. 2013. Macrofossil biofacies in the late Neogene of central Hawke's Bay: applications to palaeogeography. New Zealand Journal of Geology and Geophysics. 56(4):200–222.

Buckeridge JS, Beu AG, Gordon DP. 2018. Depositional environment of the early Pleistocene Castlepoint Formation, New Zealand: a canyon fill in situ. New Zealand Journal of Geology and Geophysics. 61(4):524–542.

Bull S, Nicol A, Strogen DP, Kroeger KF, Seebeck H. 2019. Tectonic controls on Miocene sedimentation in the Southern Taranaki Basin and implications for New Zealand plate boundary deformation. Basin Research. 31 (2):253–273. doi:10.1111/bre.12319.

Cande SC, Stock JM. 2004. Cenozoic reconstructions of the Australia-New Zealand-South Pacific sector of Antarctica. Geophysical Monograph Series. 151:5–17.

Ceballos G, Ehrlich PR, Dirzo R. 2017. Biological annihilation via the ongoing sixth mass extinction signalled by vertebrate population losses and declines. Proceedings of the National Academy of Sciences. 114(30):E6089–E6096.

Cody RD, Levy RH, Harwood DM, Sadler PM. 2008. Thinking outside the zone: high-resolution quantitative diatom biochronology for the Antarctic Neogene. Palaeogeography, Palaeoclimatology, Palaeoecology. 260:92–121.

Collins KS, Edie SM, Hunt G, Roy K, Jablonski D. 2018. Extinction risk in extant marine species integrating palaeontological and biodistributional data. Proceedings of the Royal Society, Series B. 285:20181698.

Cooper RA, Crampton JS, Raine JI, Gradstein FM, Morgans HEG, Sadler PM, Strong CP, Waghorn D, Wilson GJ. 2001. Quantitative biostratigraphy of the Taranaki Basin, New Zealand: a deterministic and probabilistic approach. AAPG Bulletin. 85(8):1469–1498.

Cooper RA, Maxwell PA, Crampton JS, Beu AG, Jones CM, Marshall BA. 2006. Completeness of the fossil record: estimating losses due to small body size. Geology. 34:241–244.

Cooper RA, Sadler PM, Hammer O, Gradstein FM. 2012. The Ordovician period. In: Gradstein FM, Ogg JG, Schmitz M, Ogg G, editors. The Geologic Time Scale 2012. Elsevier; p. 489–523.

Cox SC, Sutherland R. 2007. Regional geological framework of South Island, New Zealand, and its significance for understanding the active plate boundary. In: Okaya DA, Stern TA, Davey FJ, editors. A continental plate boundary: tectonics at South Island, New Zealand. Washington, DC: American Geophysical Union. Geophysical monograph 175; p. 19–46.

Crampton JS, Beu AG, Cooper RA, Jones CM, Marshall B, Maxwell PA. 2003. Estimating the rock volume bias in paleobiodiversity studies. Science. 301:358–360.

Crampton JS, Cody RD, Levy R, Harwood D, McKay R, Naish TR. 2016. Southern Ocean phytoplankton turnover in response to stepwise Antarctic cooling over the past 15 million years. Proceedings of the National Academy of Sciences. 113:6868–6873.

Crampton JS, Cooper RA, Beu AG, Foote M, Marshall BA. 2010. Biotic influences on species duration: interactions between traits in marine molluscs. Paleobiology. 36:204–223.

Crampton JS, Foote M, Beu AG, Cooper RA, Matcham I, Jones CM, Maxwell PA, Marshall B. 2006. Second-order sequence stratigraphic controls on the quality of the fossil record at an active margin: New Zealand Eocene to Recent shelf molluscs. Palaios. 21:86–105.

Crampton JS, Foote M, Beu AG, Maxwell PA, Cooper RA, Matcham I, Marshall BA, Jones CM. 2006. The ark was full! Constant to declining Cenozoic shallow marine biodiversity on an isolated mid-latitude continent. Paleobiology. 32:509–532.

Crampton JS, Schiøler P, Morgans H, Raine I, Roncaglia L, Fohrmann M, Reid E. 2012. Quantitative stratigraphy of the Taranaki Basin, GNS Science Data Series 17A. 56 p.

Fan J-X, Shen S-Z, Erwin DH, Sadler PM, MacLeod N, Cheng Q-M, Hou X-D, Yang J, Wang X-D, Wang Y, et al. 2020. A high-resolution summary of Cambrian to Early Triassic marine invertebrate biodiversity. Science. 367(6475):272–277.

Finnegan S, Anderson SC, Harnik PG, Simpson C, Tittensor DP, Byrnes JE, Finkel ZV, Lindberg DR, Liow LH, Lockwood R, et al. 2015. Paleontological baselines for evaluating extinction risk in the modern oceans. Science. 348:567–570.

Fleming CA. 1958. The New Zealand regional fossil record system. Geological Society of New Zealand Newsletter. 5:27–32.

Foote M, Crampton JS, Beu AG, Marshall BA, Cooper RA, Maxwell PA, Matcham I. 2007. Rise and fall of species occupancy in Cenozoic fossil molluscs. Science. 318:1131–1134.

Foote M, Crampton JS, Beu AG, Nelson CS. 2015. Aragonite bias, and lack of bias, in the fossil record: lithological, environmental, and ecological controls. Paleobiology. 41:245–265.

Gage M. 1982. Ante-natal history of the fossil record form. Geological Society of New Zealand Newsletter. 55:46–48.

Greenwood DR, Archibald SB, Mathewes RW, Moss PT. 2005. Fossil biotas from the Okanagan Highlands, southern British Columbia and northeastern Washington State: climates and ecosystems across an Eocene landscape. Canadian Journal of Earth Sciences. 42:167–185.

Hendy AJW. 2009. The influence of lithification on Cenozoic marine biodiversity trends. Paleobiology. 35(1):51–62.

Holland SM. 2010. Additive diversity partitioning in palaeobiology: revisiting Sepkoski's question. Palaeontology. 53:1237–1254.

Hornibrook NdB. 1992. New Zealand Cenozoic marine paleoclimates: a review based on the distribution of some shallow water and terrestrial biota. In: Tsuchi R, Ingle JC, editors. Pacific Neogene: environment, evolution and events. Tokyo: University of Tokyo Press; p. 83–106.

Jaramillo C, Rueda MJ, Mora G. 2006. Cenozoic plant diversity in the neotropics. Science. 311:1893–1896.

Mildenhall DC, Pocknall DT. 1984. Palaeobotanical evidence for changes in Miocene and Pliocene climates in New Zealand. p. 159–171 IN: Vogel JC (ed.) Late Cainozoic palaeoclimates of the Southern Hemisphere: proceedings of an International Symposium held by the South African Society for Quaternary Research, Swaziland, 29 August – 2 September 1983. Rotterdam: A.A. Balkema.

Mortimer N, Campbell HJ, Tulloch AJ, King PR, Stagpoole VM, Wood RA, Rattenbury MS, Sutherland R, Adams CJ, Collot J, Seton M. 2017. Zealandia: Earth's hidden continent. GSA Today. 27(3):27–35.

Nathan S. 2005. Harold Wellman: a man who moved New Zealand. Wellington, New Zealand: Victoria University Press; p. 1–272.

Pocknall DT. 1989. Late Eocene to Early Miocene vegetation and climate history of New Zealand. Journal of the Royal Society of New Zealand. 19(1):1–18.

Pocknall DT. 1990. Palynological evidence for the early to middle Eocene vegetation and climate history of New Zealand. Review of Palaeobotany and Palynology. 65(1–4):57–69.

Prebble JG, Reichgelt T, Mildenhall DC, Greenwood DR, Raine JI, Kennedy EM, Seebeck HC. 2017. Terrestrial climate evolution in the Southwest Pacific over the past 30 million years. Earth and Planetary Science Letters. 459:136–144.

Raine JI. 1992. "FRED", Fossil Record Electronic Database using BASIS. Institute of Geological and Nuclear Sciences science report 92/10: 1–107.

Raine JI, Beu AG, Boyes AF, Campbell HJ, Cooper RA, Crampton JS, Crundwell MP, Hollis CJ, Morgans HEG. 2015. Revised calibration of the New Zealand Geological Timescale: NZGT2015/1. GNS Science report 2012/39: 1–53.

Raine JI, Mildenhall DC, Kennedy EM. 2011. New Zealand fossil spores and pollen: An illustrated catalogue, 4th edition. GNS Science Miscellaneous Series, vol.4. http://data.gns.cri.nz/sporepollen/index.htm.

Raine JI, Schiøler P. 2012. Upper Cretaceous biostratigraphy of Maui-4 and Tane-1 wells, Taranaki Basin. GNS Science Report 2012/28: 1–29 + appendices.

Rattenbury MS, Isaac MJ. 2012. The QMAP 1:250 000 Geological Map of New Zealand project. New Zealand Journal of Geology and Geophysics. 55:393–405.

Reichgelt T, Kennedy EM, Mildenhall DC, Conran JG, Greenwood DR, Lee DE. 2013. Quantitative palaeoclimate estimates for early Miocene southern New Zealand:

evidence from Foulden Maar. Palaeogeography, Palaeoclimatology, Palaeoecology. 378:36–44.
Sadler P. M., Cooper R. A., Crampton J. S. 2014. High-resolution geobiologic time-lines: progress and potential, fifty years after the advent of graphic correlation. The Sedimentary Record. 12(3):4–9.
Sadler P. M., Cooper R. A., Melchin M. 2009. High-resolution, early Paleozoic (Ordovician-Silurian) time scales. Geological Society of America Bulletin. 121(5-6):887–906.
Sahoo TR, Bland KJ, Arnot MJ, Boyes AF, Funnell RH, Griffin AG, Kroeger KF, Lawrence MJF, O'Brien G, Scadden PG, Strogen DP, Town CC, Viskovic GPD. (compilers) 2017. Atlas of Petroleum Prospectivity, Southeast Province: ArcGIS geodatabase and technical report. GNS Science Data Series 23c. 1 ArcGIS geodatabase, 5 ArcGIS projects, 1 technical report.
Schiermeier Q. 2003. Setting the record straight. Nature. 424:482–483.
Strogen DP, Bland KJ, Nicol A, King PR. 2014. Paleogeography of the Taranaki Basin region during the latest Eocene-Early Miocene and implications for the 'total drowning' of Zealandia. New Zealand Journal of Geology and Geophysics. 57(2):110–127. doi:10.1080/00288306.2014.901231.
Strogen DP, Higgs KE, Griffin AG, Morgans HEG. 2019. Late Eocene - Early Miocene facies and stratigraphic development, Taranaki Basin, New Zealand: the transition to plate boundary tectonics during regional transgression. Geological Magazine. 156(10):1751–1770. doi:10.1017/S0016756818000997.
Sudlow MC, Edwards AR. 1982. Fossil record manual – 2. New Zealand Geological Survey Report NZGS. 101:1–52.
Trewick SA, Bland KJ. 2012. Fire and slice: palaeogeography for biogeography at New Zealand's North Island/South Island juncture. Journal of the Royal Society of New Zealand. 42(3):153–183. doi:10.1080/03036758.2010.549493.
Urban MC. 2015. Accelerating extinction risk from climate change. Science. 348:571–573.
Van Hinsbergen DJJ, de Groot LV, van Schaik SJ, Spakman W, Bijl PK, Sluijs A, Langereis CG, Brinkhuis H. 2015. A paleolatitude calculator for paleoclimate studies. PLoS ONE. 10(6):e0126946. doi:10.1371/journal.pone.0126946.
White EP, Morgan Ernest SK, Adler PB, Hurlbert AH, Lyons SK. 2010. Integrating spatial and temporal approaches to understanding species richness. Philosophical Transactions of the Royal Society B: Biological Sciences. 365(1558):3633–3643.
Womack T, Crampton J, Hannah M. 2018. Resolving the Cenozoic fossil record of New Zealand: unravelling macroevolution. In: Sagar M, Prebble J, editors. Abstract Volume: Geosciences 2018, Napier, New Zealand. Geoscience Society of New Zealand Miscellaneous Publication 151A: 300.