

The time-calibrated composite — A powerful tool in basin exploration

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Abstract

The Taranaki Basin has a complex geological history and biostratigraphic data are key to resolving many stratigraphic and structural problems facing the explorationist. Biostratigraphic data, however, are themselves complex and contradictory; inconsistencies in fossil ranges can be caused by incomplete sampling, misidentification, sedimentary reworking, and real variations in the distribution of species. Because of these factors, the problem of correlation is enormous when dealing with large numbers of fossil species in many wells. Quantitative stratigraphic methods address these problems by using a variety of objective or semi-objective mathematical approaches.

A quantitative biostratigraphic analysis of eight Taranaki exploration wells demonstrates that a substantial amount of new high resolution biostratigraphic information can be extracted from existing data. The range tops of 87 taxa, representing foraminifers, nannofossils, pollen, spores, and dinoflagellates, in cuttings samples have been used to derive a precise correlation of the eight wells that compares favourably with seismic correlations. The PC program, Constrained Optimisation (CONOP), which employs the principles of both graphic correlation and unitary association, has been used, and the method extended to derive a composite section that is calibrated against the time scale. Using this “time-calibrated composite”, the depositional history of the well sequences can be determined, and the stratigraphic position, age and duration of unconformities can be determined. From the eight wells studied, it appears that during the Paleocene through Oligocene interval, there were short pulses of relatively rapid deposition separated by periods of nondeposition. A regional unconformity at the base of the Eocene is revealed. The time-calibrated composite promises to be a powerful tool in basin analysis, particularly for detecting sequence boundaries.

Introduction

Drilling an exploration well is an expensive way to acquire stratigraphic data. It follows therefore, that having drilled a well or wells, it is important that the maximum amount of information be extracted from the data. In the Taranaki Basin (Figure 1), over 80 exploration wells have been drilled since 1960 and there is a wealth of stratigraphic information available for analysis. This paper discusses quantitative methods of treating the biostratigraphic data obtained from well cuttings samples in order to derive a precise correlation and depositional history, and to detect position and duration of unconformities, not available from conventional biostratigraphic analysis. An added advantage on the New Zealand scene is that most of the biostratigraphic data are already in a centralised data base - the New Zealand Fossil Record File. A formatting programme enables conversion of the raw data in the Fossil Record File to match the input requirements of the quantitative analysis programmes.

Quantitative biostratigraphic applications

A range of quantitative biostratigraphic methods is now available, and those developed and practised at the Institute of Geological and Nuclear Sciences (GNS) are summarised in Figure 2. *Biolog analysis* quantifies the relative (or absolute) abundance of taxa and groups of microfossils (mainly foraminifera) and detects depositional and environmental (oceanographic) changes through time. Quantitative *palynomorph analysis* similarly uses the relative abundance of palynomorphs to detect environmental (climatic) changes on land and changes in the terrestrial/marine interface. *Palynofacies analysis* uses the relative abundance of kerogen components for environmental analysis. All three methods provide signals for fine, intra-basinal correlation and sequence boundary detection.

Under the heading of quantitative stratigraphy is a family of methods aimed at improved correlation and zonation of

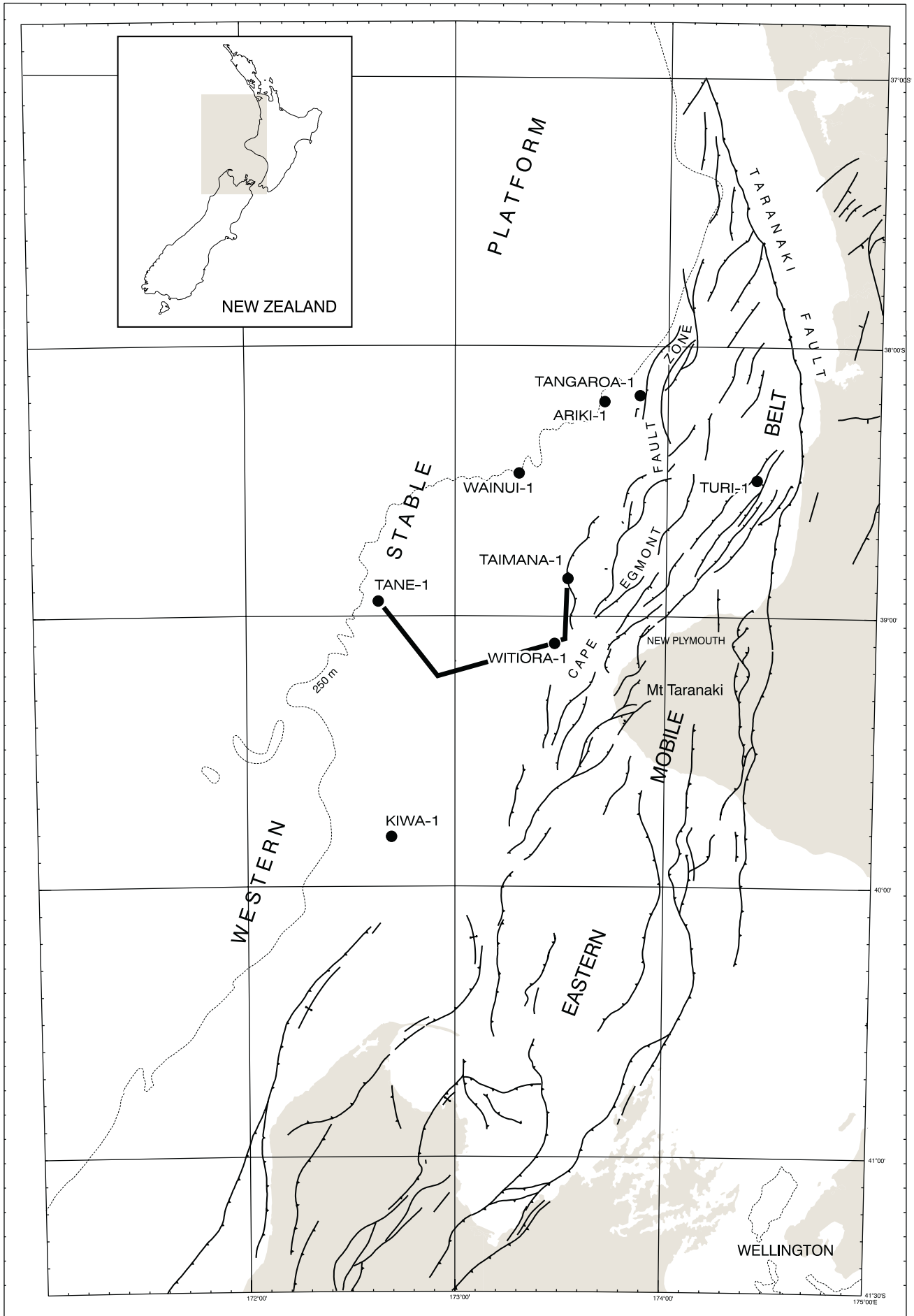


Figure 1: Taranaki Basin showing major Cenozoic faults and location of exploration wells used in the present study. The seismic profile used in Figure 4 is indicated.

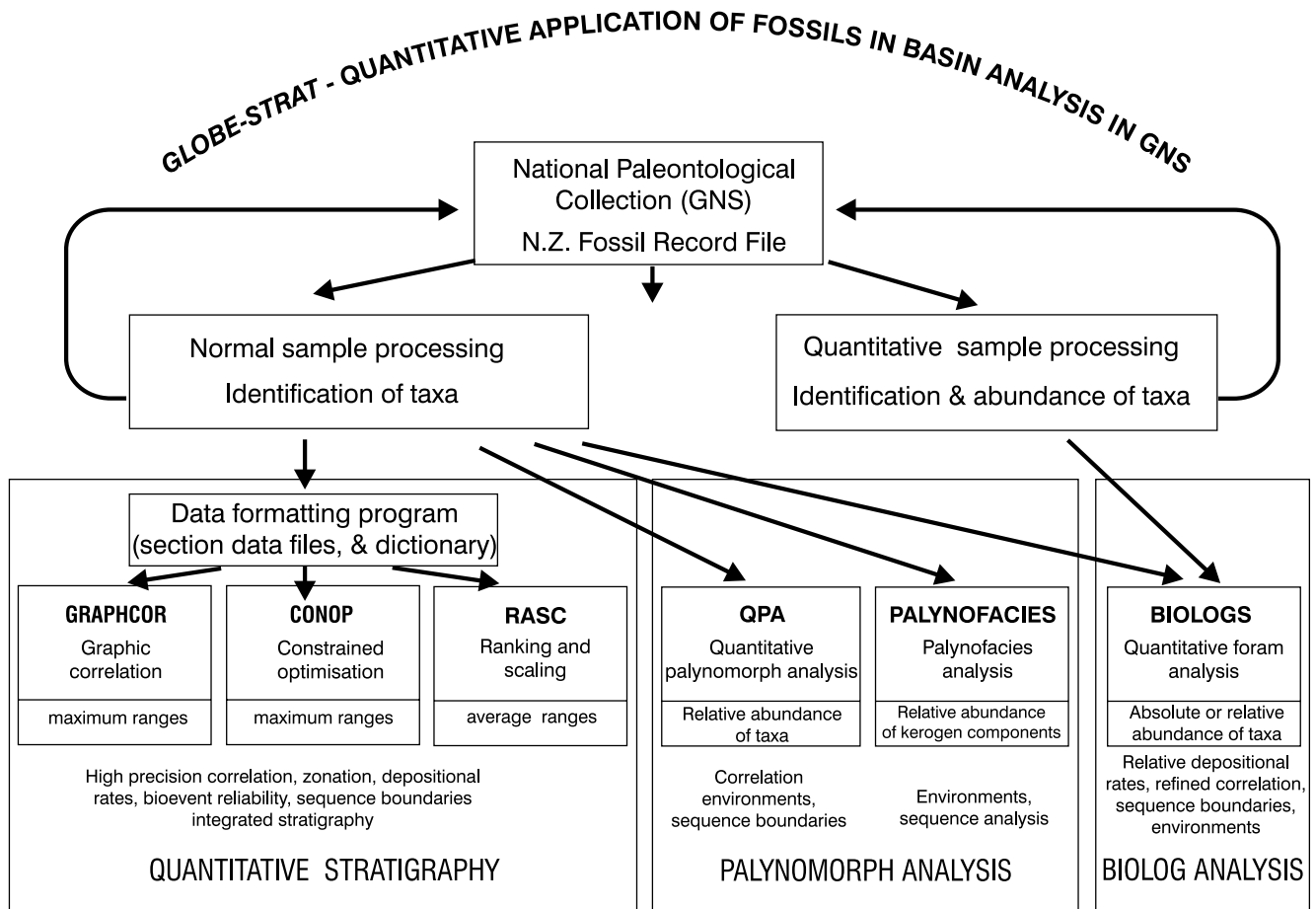


Figure 2: Quantitative biostratigraphic techniques currently employed in the Institute of Geological and Nuclear Sciences.

sedimentary successions. The most widely practised of these, particularly in industry, is *graphic correlation* which is designed to use all (or most) of the biostratigraphic events in a section rather than just those selected *a priori* as zonal index taxa, as in conventional biostratigraphy. In the process, it builds a composite section with events ordered and spaced according to their estimated 'true' order and spacing in time. The method is now well known, and is fully discussed and explained by several authors in Mann et al. (1995). When the number of events and, in particular, the number of sections, becomes relatively large, graphic correlation becomes labour-intensive, even when using a PC program such as GraphCor. It requires section-by-section correlation with the composite, in successive rounds of correlation. In contrast, an automated correlation technique developed by Kemple et al. (1995), *constrained optimisation* (PC program, *CONOP*), treats all sections simultaneously and automatically fits a correlation line. The constraining process incorporates the correlation strategies of unitary association (Geux 1991, Alroy 1994). A second automated method, *ranking and scaling* (PC program, *RASC*), uses a completely different approach and derives a probabilistic zonation and correlation scheme. The two methods are compared and applied to sequences in the Taranaki Basin by Cooper et al. (submitted). The following analysis uses only the constrained optimisation method (*CONOP*).

Quantitative stratigraphy of the Taranaki basin

The *CONOP* method has been used in a quantitative stratigraphic analysis of the Taranaki Basin. The full database

comprised the stratigraphic ranges of 493 taxa, representing foraminifera, nannofossils, dinoflagellates and miospores, in eight well sections. The wells studied were Kiwa-1, Witiara-1, Turi-1, Taimana-1, Tane-1, Wainui-1, Ariki-1, and Tangaroa-1. The full data set was culled to the 89 most reliable and commonly occurring range top events for analysis. The constrained optimisation method is described in Kemple et al. (1995) and its terminology and application in the Taranaki Basin is discussed by Cooper et al. (submitted). In this paper we briefly outline the method and describe some of its outputs, as applied to the Taranaki Basin. In particular, the current work draws attention to a), the high-resolution correlation of sections, b), the derivation of a time-calibrated composite, and c), the application of this composite to analysis of depositional rates and detection of previously unrecognised unconformities in the well sections. Further outputs, not discussed here, include an evaluation of event reliability, well net discordance and a probabilistic zonation for the Taranaki Basin (Cooper et al. submitted). For a full description of the stratigraphy, basin development and history, structural evolution, and petroleum potential of the Taranaki Basin, see King and Thrasher (1995).

CONOP, like graphic correlation, uses the order and spacing of stratigraphic events, such as taxon range-end events. It compares all sections simultaneously and fits a multi-dimensional line of correlation to all points in all sections. Therefore, unlike graphic correlation, it does not require the selection of an initial 'standard section'. *CONOP* finds that correlation scheme, out of the huge number of possible

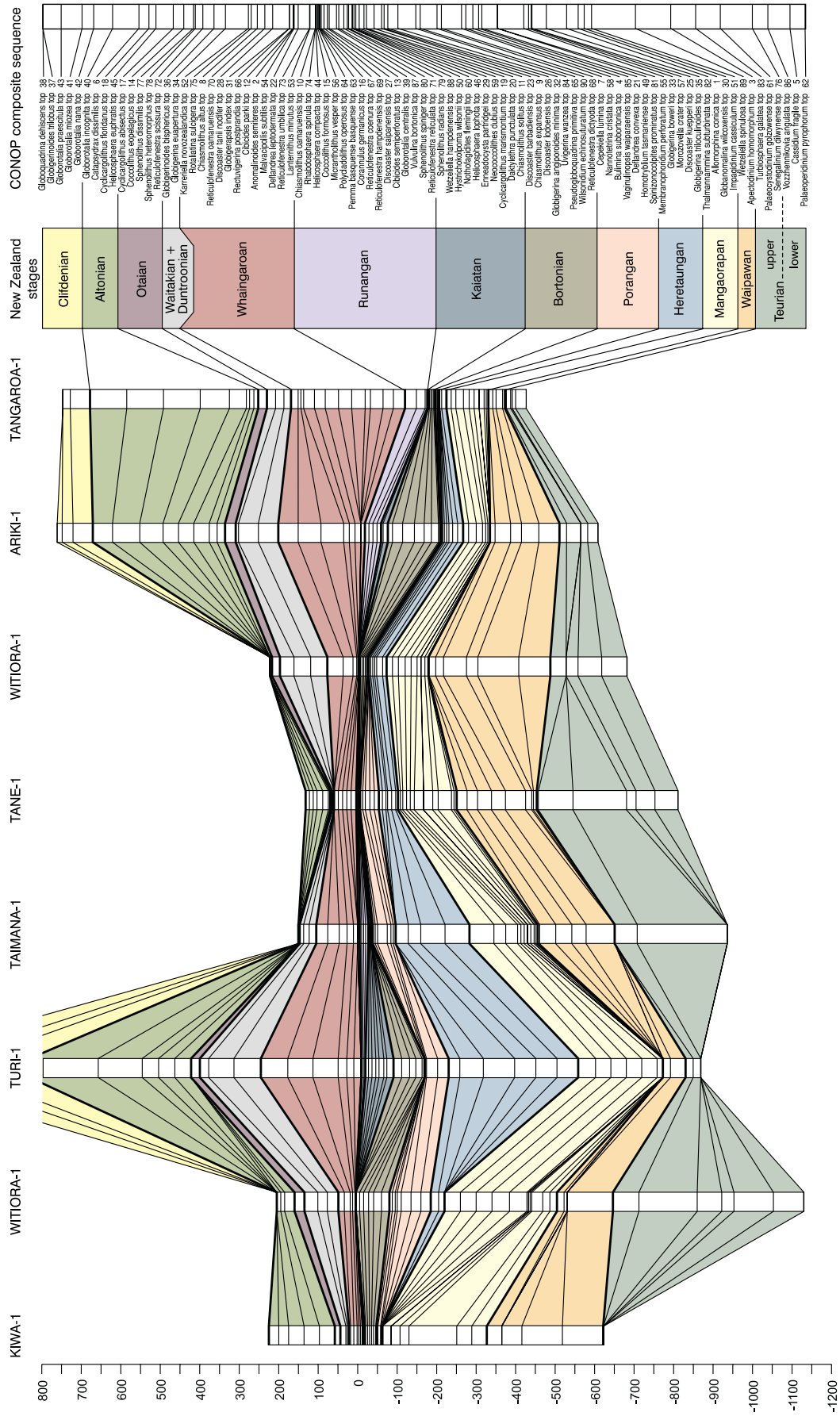


Figure 3: Correlation of well sections by Constrained Optimisation (CONOP). All events are biostratigraphic last appearance events and their positions in the well successions are the 'placed levels' (i.e. adjusted levels). A five-point moving average has been used to separate events that would otherwise be clustered at the same level, and most lines represent a single event. Zero level is at the base of the Tikorangi Formation.

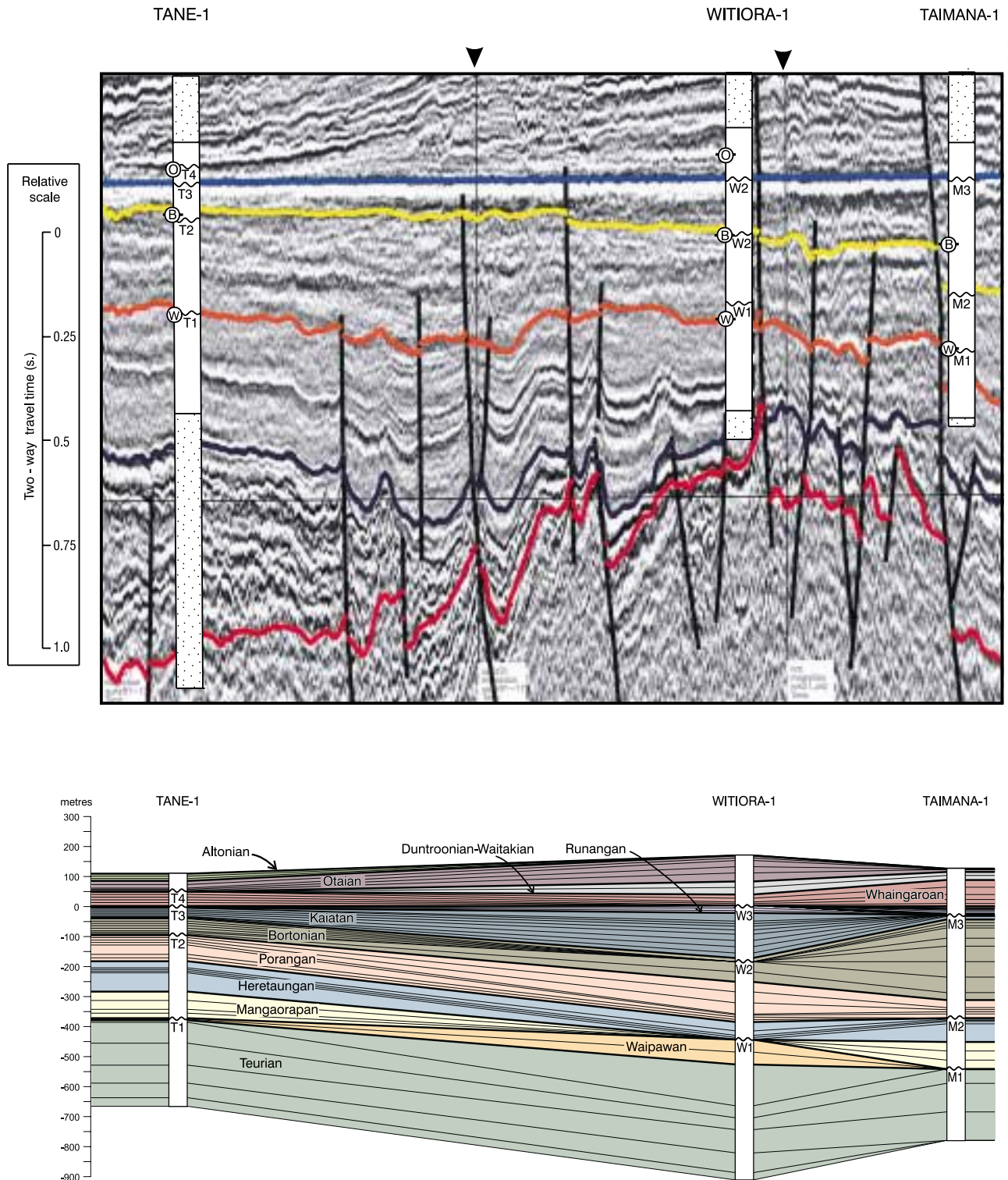


Figure 4: Seismic profile through the three wells, Tane-1, Witiora-1, and Taimana-1 (4a), compared with CONOP correlation of the same wells (4b), derived from Figure 3. The sampled interval (clear portion of well columns) extends from Paleocene to early Miocene. The seismic profile (see Figure 1) was processed by GEOQUEST to level out the top of the Tikorangi Formation. Arrowheads at the top indicate legs in the seismic lines. Unconformities in the CONOP correlation are from the age-depth plots for each well (Figure 7). Selected CONOP correlation levels (W, base Waipawan; B, a level low in the Porangan; O, base Otaian) are shown in the well columns on the seismic profile. These, and the unconformities, have been positioned in the columns on the seismic profile using the metre scale in 4b); they have not been corrected for local (within hole) differences in velocity. Note that the mean seismic velocity for the sampled interval in Witiora-1 is appreciably higher than the same interval in the other two wells.

correlation schemes, which incurs the smallest net readjustment (extension) of taxon range ends among all sections. Similarly, the composite sequence is that sequence which causes the smallest net disruption when the ranges of taxa in each of the well sections are adjusted to match it. The composite represents the best estimate of the 'true' order and spacing of events in time, as represented among the wells.

Like graphic correlation, CONOP seeks the maximum ranges of taxa to build its composite sequence, which compares well with that derived by conventional graphic correlation ($r = 0.9205$, Cooper et al. submitted).

Composite sequence and correlation of well sections

The CONOP model for correlation of well sections is shown in Figure 3. It employs a relatively large number of events (89) and provides an order of magnitude more precision than can be obtained by conventional biostratigraphy. The correlation lines join the CONOP-placed levels for all events in all sections. A five-point moving average has been used to separate events that would otherwise be clustered at the same level. Zero level is at base of the Tikorangi Formation. The age assignments in some wells modify earlier assignments. Note that CONOP extends stratigraphic ranges of taxa (like graphic correlation) and stage boundaries in many wells are placed a little higher than in the original biostratigraphy. Relative changes in thickness from well to well are highlighted, as are local unconformities and highly condensed intervals. The Whaingaroan, for example, which is a long stage, is relatively thick in Tangaroa-1, Ariki-1 and Turi-1, but thin in the other wells. The Kaiatan, a short stage, is missing or condensed in all wells except Witiorea-1. An otherwise undetectable Bortonian intra-stage unconformity (or condensation) is seen in Witiorea-1.

The fine control on correlation that can be derived from a CONOP analysis is illustrated by a comparison with the seismic profiles for the same interval. Figure 4 shows a seismic profile joining Tane-1, Witiorea-1 and Taimana-1, and the equivalent fence diagram based on the CONOP correlation (Figure 3). The seismic profile is composed of three legs (Figure 1), derived from two seismic grids. The seismic lines have been interpreted using GEOQUEST software and, to make the comparison easier, are replotted with the reflector representing the base of the Tikorangi Formation levelled out. The scale at left is therefore relative only.

In Figure 4a, five seismic horizons have been picked out, the uppermost one being the base of the Tikorangi Formation. The first two seismic picks (coloured yellow and orange) below the base of the Tikorangi can be located within the sampled interval in each of the three wells. For comparison, also shown is the location in each of the three wells, of an equivalent correlation level (labelled W and B) derived from the CONOP correlation diagram (Figure 4b). There is a close correspondence between the seismic and CONOP correlations for the two wells, Tane-1 and Witiorea-1. In contrast, in Taimana-1, the CONOP correlation is at variance with the

seismic picks. If the CONOP correlation levels are correct, then the two seismic picks are each placed too low, possibly caused by misinterpretation of the offset on the major fault lying immediately to the west. Another possible cause of the discrepancy is the poorer quality of the seismic data in this (eastern) leg, as compared with the two legs to the west. The problem needs further investigation but highlights the fact that quantitative biostratigraphic analysis can provide high precision and independent tests of seismic interpretations.

Time-calibrated composite - a new tool in basin exploration

Neither GraphCor nor CONOP will detect basin-wide depositional hiatuses, present in all sections, unless an external frame of reference is used. Many of the biostratigraphic events used in the analysis are known from other depositional basins in New Zealand and have well established New Zealand chronostratigraphic ages. The New Zealand stages have been calibrated against the international time scale and the geochronological time scale (Morgans et al. 1966), so that the age of events, in millions of years, can be derived. The known age for 57 of the events are plotted against their levels in the Taranaki composite section (Figure 5). The events define a curvi-linear distribution, except for five anomalous events that are ignored. The smoothed regression line is a locally-estimated sum of squares (LOESS) regression function (Chambers et al. 1983). Deviations from the line are caused by taxa ranging higher in the Taranaki Basin than elsewhere or reworking of taxa in the cuttings

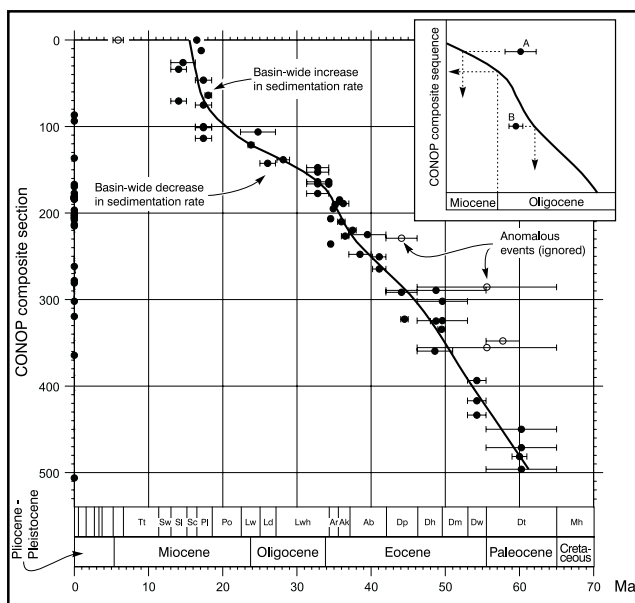


Figure 5: Construction of the time-calibrated composite. Events in the CONOP composite for the Taranaki Basin (y-axis) are plotted against their age known from elsewhere in New Zealand (see text for explanation). Open circles are anomalous events, and are ignored. The regression line enables events to be located in the time scale (x-axis), producing a "time-calibrated composite". Similarly, using the regression, the stage boundaries in the time scale can be accurately projected into the CONOP composite for the Taranaki Basin. The inset box demonstrates the method of projecting events and boundaries (Cooper et al. submitted). Age calibration follows Morgans et al. (1996).

samples (range tops too high), or incomplete stratigraphic ranges of taxa in the Taranaki holes (range tops too low). Taxon misidentification, another cause of scatter, is likely to have been minimised by the severe culling of events.

The regression allows the composite section to be rescaled to an approximately linear time scale that is independent of basin-wide changes in depositional rate. It is referred to as a *time-calibrated composite* (Cooper et al. submitted). It also enables stage boundaries to be projected into the composite from the time scale axis. These boundaries are those used in the correlation diagrams (Figures 3, 5) and age-depth plots (Figures 6, 7). The time-calibrated composite is a powerful tool in basin analysis and exploration, and is here applied to measuring depositional rates in the well sections.

The regression also reveals basin-wide changes in depositional rate. Flattening of the curve in the Oligocene and earliest Miocene coincides with deposition of the Tikorangi Limestone and Taimana Formation (lime mudstone) in deep water. Steepening of the curve in the later part of the early Miocene represents an influx of clastic detritus from the east produced by tectonic activity associated with the onset of plate boundary activity.

Age-depth plots, depositional rates

In the CONOP best-fit correlation scheme, taxon ranges in each well are extended as necessary to accord with those in the composite section. These 'placed levels' are estimates of the 'true' taxon ranges in the basin. When the placed level for each event in a well is plotted against its level in the time-calibrated composite, a composite age-depth plot for the well

is obtained. This gives a remarkably precise estimate of depositional rate in the well. As an example, the age-depth plot for Tangaroa-1 (Figure 6) shows that depositional rate ranges from 23 metres/m.y. in the late Oligocene-early Miocene when fine grained carbonates predominate, to 500 metres/m.y. in the later part of the early Miocene, when there was a flood of clastic detritus into the basin resulting from the onset of plate boundary activity in the east.

The age-depth plots reveal many previously unrecognised unconformities and condensed intervals (Cooper et al. submitted). In this paper the term unconformity is used in a general sense, to include both unconformities and highly condensed intervals. In the eight well sections studied, the sedimentary record appears to be much less complete than previously thought. Six unconformities are present in the Tangaroa-1 section (Figure 6), including four in the Eocene and Paleocene that had not been detected previously. The two lowest of these are very closely spaced and may represent a single unconformity. The duration of unconformities can be estimated with greater precision than by conventional biostratigraphy. In the case of Tangaroa-1, Figure 6 shows that of the 28 m.y. from mid-Paleocene to late Eocene time, 16 m.y. is represented either by stratigraphic gaps or highly condensed intervals.

From Figure 6, the age of the base of the Tikorangi Formation in Tangaroa-1, previously not tightly constrained within the Whaingaroan Stage, can be estimated at 33 m.y. (basal Oligocene), well above the base of the Whaingaroan, whereas it lies almost exactly at the base of the Whaingaroan in all other sections studied. In this drill hole the unconformity at the base of the Formation, seen in all other drill hole sections except for Turi-1, is not present.

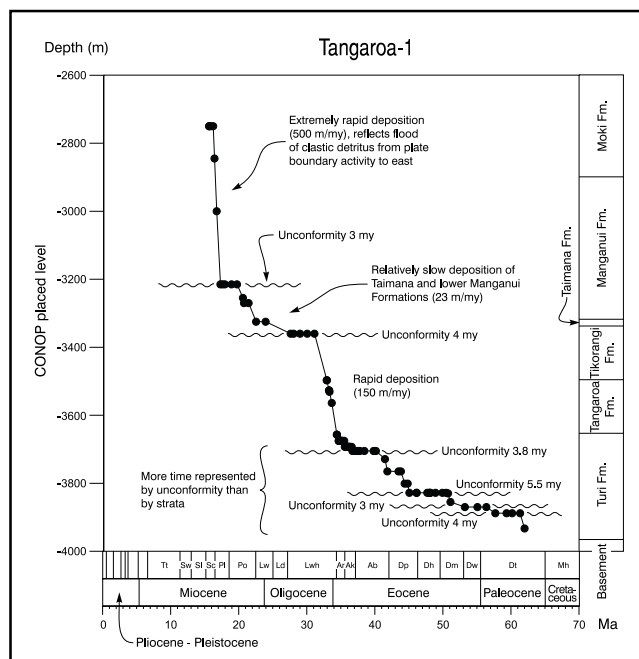


Figure 6: Age-depth plot for Tangaroa-1 well. Using the time-calibrated composite (X-axis), biostratigraphic events in the Tangaroa-1 well, as placed by CONOP, define a line with distinct terraces that represent unconformities or condensed intervals. Depositional rate is determined by the slope of the line.

When the axes of the age-depth plots are reversed, the alignment of unconformities is more easily seen. As examples, the age-depth plots for Tane-1, Witiora-1, and Taimana-1 are compared (Figure 7). Correlation of unconformities from well to well should be done in the context of a regional analysis (e.g. King and Thrasher 1995, Enclosure 5) and those indicated in Figure 7 are tentative. The major unconformity in the latest Eocene to early Oligocene, however, is well defined and is inferred to be the Marshall Paraconformity, following King and Thrasher (1995). The unconformity near the base of the sampled interval, in the early Eocene, is poorly controlled in Taimana-1 (M1), although it is well controlled in Tane-1 (T1) and Witiora-1 (W1; Cooper et al. submitted). It is present in many of the wells and appears to be of basin-wide extent. It may coincide with the regional base-level drop at the base of the Waipawan Stage (basal Eocene) recognised by King et al. (1991). The figure also suggests that the Tikorangi Formation is slightly time-transgressive, becoming older in the direction of the more off-shore well, Tane-1.

It is not determined from the plots (Figures 6, 7) whether the unconformities represent intervals of erosion or non-deposition. From his knowledge of the Taranaki Basin, Dr Peter King (pers. comm.) considers most of the putative unconformities detected by CONOP represent intervals of

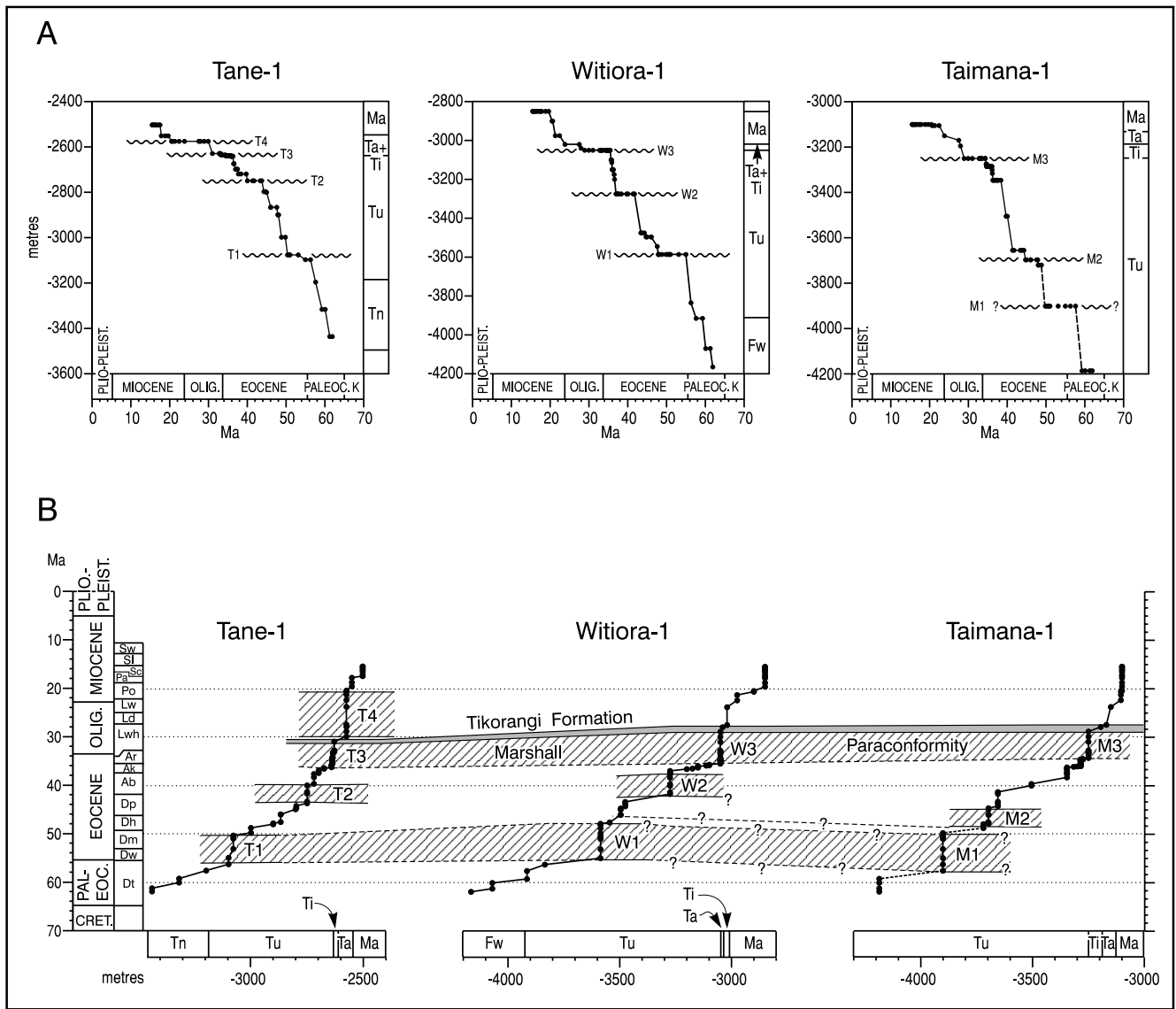


Figure 7: Age-depth plots for Tane-1, Witiara-1 and Taimana-1, using the time-calibrated composite as in Fig. 6. In 7a they are shown in the conventional way (see Figure 6) wherein unconformities and condensed intervals are indicated by terraces in the regression line. In 7b the x- and y-axes are reversed, enabling correlation of unconformities. Abbreviations for lithostratigraphic units as follows: Fw = Farewell Formation; Ma = Manganui Formation; Ta = Taimana Formation; Ti = Tikorangi Formation; Tn = Tane Member; Tu = Turi Formation.

non-deposition. The picture of depositional history is thus one of relatively short pulses of rapid deposition separated by periods of non-deposition.

Note that whereas some of the unconformities, such as the Marshall Paraconformity, are associated in the seismic profile with a prominent reflector, others, such as the early Eocene one, are not.

Although the model for depositional history represented by Figure 7 is tentative, and needs to be corroborated by further work, it suggests that the time-calibrated composite derived from CONOP analysis can be used to achieve a remarkable level of precision in detection and dating of unconformities and in estimating depositional rates, not achievable by conventional biostratigraphy. This should be useful for interpretation of major sequence boundaries.

Conclusions

Automated quantitative stratigraphic techniques enable the following:

1. A large amount of biostratigraphic information can be extracted from existing well and onshore section samples, beyond that already recovered by conventional techniques. No additional cost for data acquisition is necessary. Large data sets can be processed quickly.
2. There is a significant improvement in the resolution and precision of biostratigraphic correlation and dating of strata, formation boundaries and facies changes, even when based on relatively low quality data such as cuttings samples. Seismic correlations can be independently tested.
3. From age-depth plots based on the time-calibrated composite, precise depositional rates for the well sections

can be derived, and the age and duration of unconformities estimated. This information should improve the reliability and accuracy of sequence analysis of the basin.

4. The composite sequence provides the most detailed biostratigraphic 'scales' available for the basin. The correlation schemes based on them enable a time dimension to be superimposed on seismic profiles.

The future

Some directions for future work that should further improve the reliability and usefulness of the quantitative stratigraphic techniques in the Taranaki Basin are:

1. Build, and improve the reliability of, the composite section by adding more drill hole sequences, and adding onshore measured sections.
2. Extend the composite section by adding Miocene and Pliocene data, particularly from onshore (surface) sections.
3. Develop the time-calibrated composite and age/depth plots to more accurately correlate unconformities, track depositional rates and relate to sequence boundaries.
4. Use the quantitative techniques to improve understanding of the effect of environment (including depositional depth) on the distribution of fossils.
5. Quantitatively assess the reliability of biostratigraphic events, such as by assignment of confidence limits on stratigraphic ranges, in order to assist in the evaluation of rival correlation schemes.
6. Integrate with seismic and e-log data to add a time dimension to seismic profiles and physical stratigraphic markers.

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References

- Alroy, J. 1994. Appearance event ordination: a new biochronologic method. *Paleobiology* 20: 191-207.
- Chambers, J.M., Cleveland, W.S., Kleiner, B., Tukey, P.A. 1983. *Graphical methods for data analysis*. Belmont, California, Wadsworth, 395 p.
- Cooper, R.A., Crampton, J.S., Raine, J.I., Gradstein, F.M., Morgans, H.E.G., Sadler, P.M., Strong, C.P., Waghorn, D., Wilson, G.J. submitted. Quantitative biostratigraphy of the Taranaki Basin, New Zealand - a deterministic and probabilistic approach. *AAPG Bulletin*.
- Geux, J. 1991. *Biochronological Correlations*. Springer-Verlag, Berlin, 250 p.
- Kemple, W.G., Sadler, P.M., Strauss, D. J. 1995. Extending graphic correlation to many dimensions: stratigraphic correlation as constrained optimisation. Pp. 65-82 *in* Mann, K.O., Lane, H.R., Scholle, P.A. (eds) *Graphic correlation*. SEPM Special Publication 53.
- King, P.R., Naish, T.R., Browne, G.H., Field, B.D., Edbrooke, S.W., 1999. Cretaceous to Recent sedimentary patterns in New Zealand. *Institute of Geological and Nuclear Sciences Folio Series 1*: 1-30 + 1 enclosure.
- King, P.R., Thrasher, G.P. 1996. Cretaceous-Cenozoic geology and petroleum systems of the Taranaki Basin, New Zealand. *Institute of Geological and Nuclear Sciences Monograph 13*: 1-243.
- Mann, K.O., Lane, H.R., Scholle, P.A. 1995. *Graphic correlation*. SEPM (Society for sedimentary geology) Special Publication 53. 263 p.
- Morgans, H.E.G., Scott, G.H., Beu, A.G., Graham, I.G., Mumme, T.C., St George, W., Strong, C.P. 1996. *New Zealand Cenozoic timescale (version 11/96)*. Institute of Geological and Nuclear Sciences Science Report 96/38: 1-12.

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