Petrologic evidence for earliest Miocene tectonic mobility on eastern Taranaki Basin margin

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Abstract
At Gibsons Beach on the west coast of central North Island, the earliest Miocene (Waitakian) Otorohanga Limestone, the top-most formation in the Te Kuiti Group, is unconformably overlain on an undulating, locally channelised erosion surface by the Early Miocene (Otaian) Papakura Limestone at the base of the Waitemata Group. The basal facies of the Papakura Limestone is a conglomerate composed exclusively of tightly packed pebble- to cobble-sized clasts of skeletal limestone sourced from the underlying Otorohanga Limestone. This petrographic and geochemical study demonstrates that the Otorohanga Limestone was partially lithified during marine and shallow-burial cementation at subsurface depths down to a few tens of metres prior to uplift, erosion and cannibalisation of the limestone clasts into the Papakura Limestone. Strontium isotope dating of fossils from both the Otorohanga and Papakura Limestones at Gibsons Beach yield comparable ages of about 22 Ma, close to the Waitakian/Otaian boundary, indicating very rapid tectonic inversion and erosion of the section occurred in the earliest Miocene. We envisage the clasts of Otorohanga Limestone were sourced from a proximal shoreline position and redeposited westwards by episodic debris flows onto a shallow-shelf accumulating mixed siliciclastic-skeletal carbonate deposits of the Papakura Limestone. Subsequent burial of both limestones by rapidly accumulating Waitemata Group sandstone and flysch instigated precipitation of widespread burial cements from pressure dissolution of carbonate material at subsurface depths from about 100 m to 1.0 km. The vertical tectonic movements registered at Gibsons Beach can be related to the oblique compression associated with the development of the Australian-Pacific plate boundary through New Zealand at about this time and coincide with overthrusting of basement into Taranaki Basin between mid-Waitakian (earliest Miocene) and Altonian (late Early Miocene) times.

Keywords Taranaki Basin; Otorohanga Limestone; Te Kuiti Group; Papakura Limestone; Waitemata Group; tectonics; cannibalisation; diagenesis; Oligocene; Waitakian; Miocene; Otaian

Introduction
Globally, carbonate deposits form important hydrocarbon reservoirs. In Taranaki Basin one such reservoir is the carbonate-dominated Tikorangi Formation of latest Oligocene - earliest Miocene age (Waitakian) (Hood et al. 2003a,b,c, 2004a). On the onland eastern margin of Taranaki Basin the age equivalent carbonate deposit is the Otorohanga Limestone, the topmost formation of the Te Kuiti Group (e.g. Kear and Schofield 1978; Nelson 1978). At Gibsons Beach, on the west coast of central North Island (Fig. 1), the Otorohanga Limestone is unconformably overlain by the Early Miocene (Otaian) Papakura Limestone, the basal formation of the Waitemata Group (Fig. 2). The Papakura Limestone is unique at this locality because it comprises a spectacular limestone conglomerate composed of packed pebble- to cobble-sized clasts, apparently derived from the underlying Otorohanga Limestone.

The aim of this study is to investigate the origin and significance of this basal limestone conglomerate given the fact that limestone clasts of any sort are a rare contributor to sedimentary deposits because they are normally dissolved completely during weathering. To achieve this we integrate field, petrographic (standard, stained and cathodoluminescent (CL) modes) and geochemical (stable oxygen ($\delta^{18}O$) and carbon isotopes ($\delta^{13}C$), strontium isotopes ($^{87}Sr/^{86}Sr$ ratios), trace elements – Ca, Na, Mg, Mn, Fe, Sr, and carbonate analyses) data for the Otorohanga Limestone and Papakura Limestone, including the limestone clasts in the latter. In this paper we summarise only the key information, and the raw data are available on request.

Local stratigraphy
At Gibsons Beach (Fig. 1B) the Otorohanga Limestone consists of about 8 m of horizontal and cross-bedded,

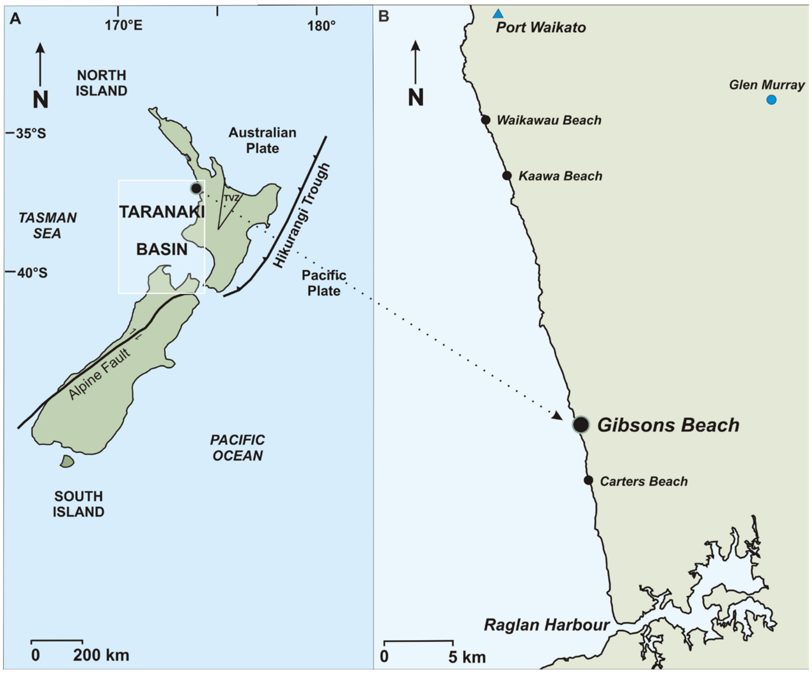

Fig. 1: *(A) Location of Taranaki Basin and the modern Australian/Pacific Plate Boundary through New Zealand. Gibsons Beach is shown by the black dot in the northeast corner of Taranaki Basin. The dashed arrow links the location of Gibsons Beach to that shown in (B) along the eastern margin of Taranaki Basin. A basic stratigraphic column is shown for the Gibsons Beach section. TVZ, Taupo Volcanic Zone.*

flaggy, extremely well cemented, pure skeletal limestone (Fig. 3A). The limestone sits conformably on the Waitakian Waitomo Sandstone, a calcareous glauconitic fine sandstone (Fig. 2) (Kear 1966, White and Waterhouse 1993). The upper surface of the Otorohanga Limestone, corresponding to the top of the Oligocene – earliest Miocene Te Kuiti Group, is marked by a sharp, smoothly undulating to sometimes channelised erosion surface (Fig. 3B), in places cutting down as deeply as the underlying Waitomo Sandstone (Hayward and Brook 1984).

The overlying early Miocene Waitemata Group at Gibsons Beach comprises the Papakura Limestone and Gibson Siltstone (Fig. 2). The Papakura Limestone consists of up to 8 m of bedded, often channelised conglomerate composed entirely of pebble- to cobble-sized clasts of limestone (Fig. 3C). The limestone clasts are typically rounded, extremely indurated and tightly packed (Fig. 3D). Many clasts have fitted or interpenetrating margins indicative of pronounced pressure dissolution (Fig. 3E). They sit in a variably muddy to sandy shelly matrix (Fig. 3F). Above the Papakura Limestone the Gibson Siltstone comprises a basal sandstone facies overlain by thick muddy flysch.

Limestone petrography - General

Otorohanga Limestone

Rocks comprise a spectrum of fine to very coarse and pure (up to 98% $CaCO_3$) skeletal-rich grainstones through packstones (Fig. 4A,B). Skeletons are dominated by bryozoan, echinoderm and bivalve debris. Calcareous red algae and large benthic foraminiferal species are important contributors in the lower and mid stratigraphic sections with planktic foraminifera increasing to modest proportions in the upper levels. Formerly aragonitic bivalves are evidenced in localised beds inland of Gibsons Beach. Limited siliciclastics comprise very fine quartz and feldspar and occasional glauconite infills and pellets. Fabrics are moderately open (15% pore volume) to tight and pressure dissolved (~5% pore volume).

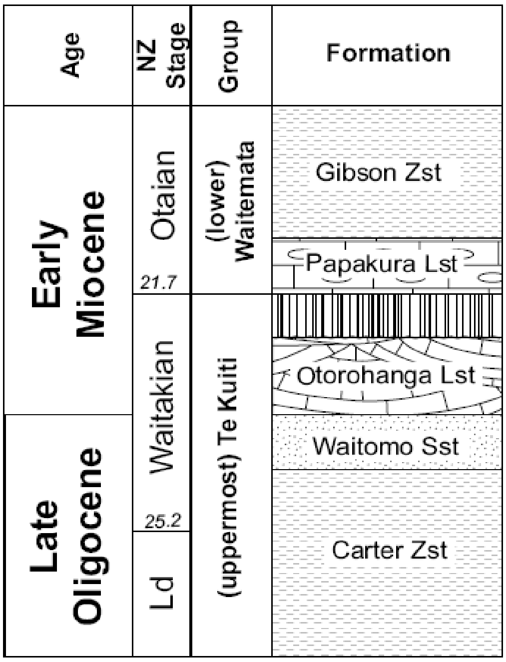

Fig. 2: *Simplified chronostratigraphy for lithologies occurring at Gibsons Beach, west coast central North Island. New Zealand stages after Cooper (2004). L, Late.*

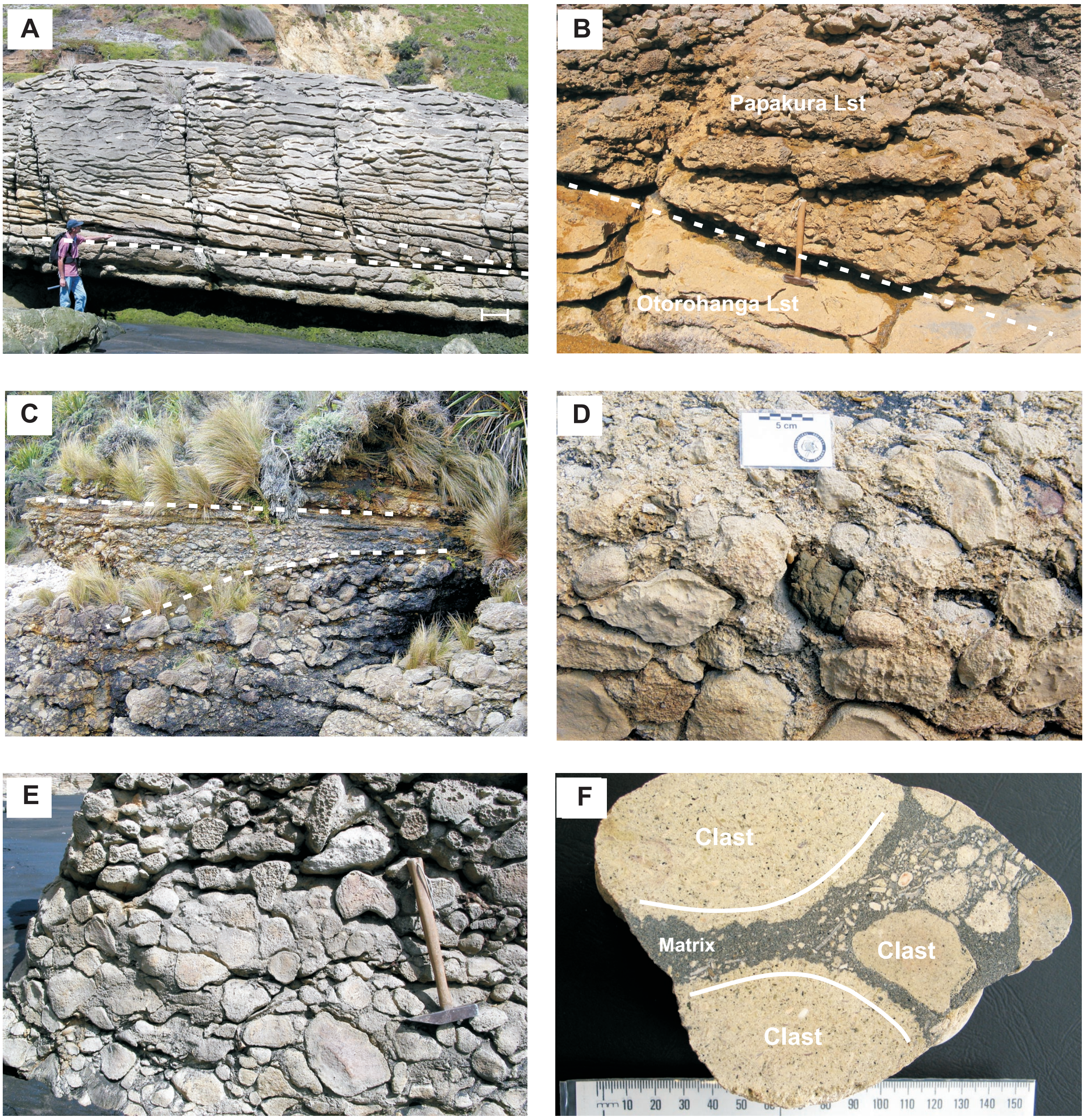

Fig. 3: **(A)** *The gently cross-bedded and flaggy Waitakian-aged Otorohanga Limestone, northern Gibsons Beach.* **(B)** *The sharp truncated erosional contact (dashed line) between the Otorohanga Limestone and overlying Papakura Limestone.* **(C)** *Bedded units of the Papakura Limestone which pinch out (dashed lines) suggestive of localised channel fill.* **(D)** *Papakura Limestone showing variably rounded limestone clasts set in a coarse shell-hash matrix. A rare clast of Waitomo Sandstone is shown.* **(E)** *The Papakura Limestone showing tightly imbricated clasts of limestone with fitted fabrics. Clasts show no obvious signs of breakage or deformation and point to significant competency at the time of deposition.* **(F)** *Slabbed surface of Papakura Limestone showing tight, dense, well-cemented clasts of Otorohanga Limestone set in an often shelly matrix. The irregular pitted clast outlines are suggestive of meteoric exposure and chemical weathering prior to redeposition.*

Papakura Limestone – limestone clasts

Limestone (micro)clasts are skeletal-rich (poorly washed) grainstones and less commonly packstones (Fig. C,D). Grainstones are tightly packed and dominated by coarse bryozoan, large benthic foraminifera, and echinoderm fragments (Fig. 4E). Few siliciclastics are present and comprise quartz, feldspar, and some glauconite. Moderately tight poorly-washed grainstones to packstones are commonly echinoderm-rich with conspicuous planktic and small benthics species with lesser bryozoan fragments (Fig. 4F). Some bivalves and rare brachiopod fragments occur. Modest quantities of glauconitic can occur as infills and as pellets. Intergranular micrite, characteristically aggraded to microspar, dominates interskeletal areas.

Papakura Limestone - matrix

Matrix composition is variable but is generally either skeletally or siliciclastic dominated (Fig. 4G, H). Skeletally dominated matrix comprises an extremely

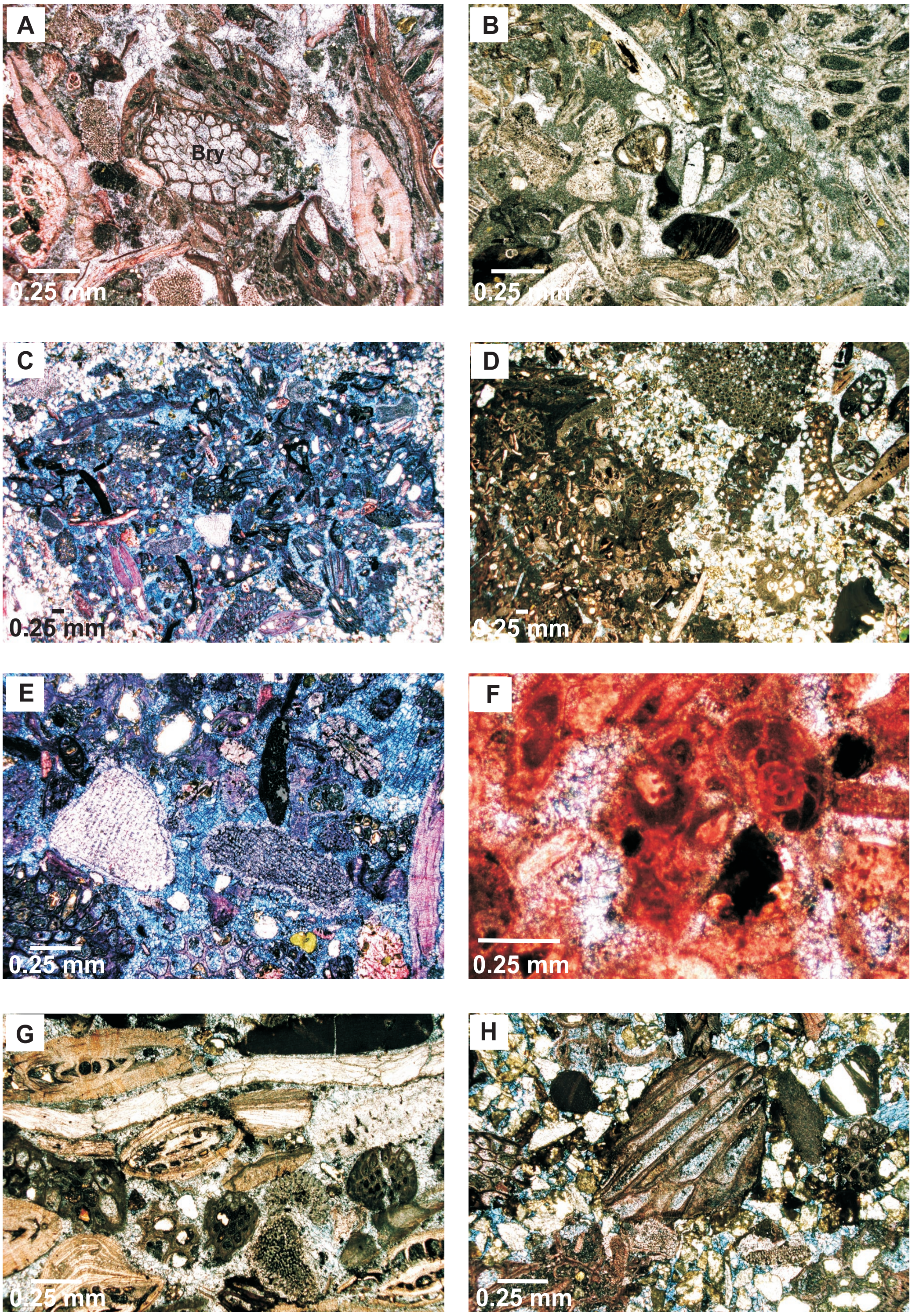

Fig. 4 : *General photomicrographs, as seen under plane-polarised light (PPL), of representative stained thin sections from the Otorohanga Limestone* **(A,B)***, Te Kuiti Group, and Papakura Limestone clasts* **(C-F)** *and matrix* **(G,H)***, basal Waitemata Group.* **(A)** *Moderately open fabriced pure bryozoan, benthic foram-rich (Amphistegina and Lepidocyclina), echinoderm and bivalve grainstone set in a dominantly nonferroan (pink) calcite cement.* **(B)** *Moderately open fabriced coarse bryozoan, echinoderm, benthic foram, bivalve packstone.* **(C)** *Low magnification view of a bryozoan, echinoderm, benthic foram dominated grainstone clast set in a fine siliciclastic dominated matrix. Blue stain indicates ferroan sparry calcite.* **(D)** *Low magnification view of a bryozoan, echinoderm, benthic foram, bivalve poorly washed grainstone to packstone clast (left) set in a extremely coarse skeletal and fine siliciclastic mixed matrix.* **(E)** *Close-up of a moderately open bryozoan, echinoderm, benthic foram grainstone dominantly cemented by ferroan calcite.* **(F)** *Close-up view of a bivalve, benthic foram, and echinoderm rich poorly washed grainstone. Note "fury" fringing cement coating skeletal grains.* **(G)** *Coarse packed skeletal-rich matrix comprising large benthic foram species, echinoderm, bivalves, red alage, and brachiopod fragments set in a ferroan calcite cement.* **(H)** *Siliciclastic-rich matrix composed of mainly quartz and feldspar grains including coarse skeletal garments together cemented by ferroan calcite cement.*

coarse shell-hash of large benthic foraminifera (*Amphistegina* sp.), bryozoans, calcareous red algae, serpulids, some echinoderms, rare brachiopods with a few siliciclastic grains and rare glauconite pellets (Fig. 4G). Overall fabrics are moderately open while grain contacts are pressure dissolved. Micrite occurs in some intragranular pores, mainly bryozoan zoeccia. siliciclastic-rich matrix comprises very fine to quartz with lesser feldspar and contains some quantity of skeletal debris (Fig. 4H).

Limestone petrography - cements

Otorohanga Limestone

Despite much cement complexity, some general comments can be made. First formed cements are fringing nonferroan calcite forms (Fig. 5A,B). They are commonly dirty/inclusion-rich and have typically isopachous bladed habits. Pressure dissolution effects are often visible. Their CL is commonly non to moderately bright red/orange. Biomouldic porosity fill of former aragonitic bivalves is by nonferroan calcite (Fig. 5C). Fringe syntaxial rim cements about echinoderms are typically non-ferroan and display serrated growth comprising an often thick dull inner, bright mid-zone, and a non/dull luminescent outer (Fig. 5D). Pressure dissolution has in some instances truncated these syntaxial rims. Final pore occlusion is by dominantly ferroan (blue stained) (Fig. 5A, D), occasionally nonferroan (pink stained) (Fig. 4A), (micro)equant calcite with a non- to dull-CL.

Papakura Limestone – limestone clasts

A range of cement fabric types are evident. The first generation comprises nonferroan calcite fringe cements occurring as a spectrum of inclusion-rich/dirty bladed to less commonly dog-toothed to more fibrous forms (Fig. 5E). Their CL shows a range of non, dull or moderate luminescence (Fig. 5F). These fringe cements show clear evidence of pressure dissolution. Syntaxial rim cements are poorly to moderately-well developed, have an initial nonferroan mineralogy (Fig. 5G), contain a spired zonation consisting of a dominantly thicker non inner zone and a thin bright outer zone (Fig. 5H). The second generation where present (i.e. grainstones) comprises typical burial type (micro) equant calcite which show a range of nonferroan to ferroan mineralogies with moderately bright to dull luminescence respectively (Fig. 4C,E; 5E-H).

Papakura Limestone - matrix

A paucity of fringe cements about skeletal grains within the matrix contrasts to the limestone clasts in the Papakura and Otorohanga Limestones. Syntaxial rim cements are poorly developed. Equant pore occluding cements are ferroan calcite (Fig. 4G,H) and exhibit a dull or patchy brighter CL that becomes dull poreward.

Diagenetic sequence of events

Petrography has enabled comparison of the Otorohanga Limestone with the limestone clasts in the overlying Papakura Limestone to ascertain that the Otorohanga Limestone is the most likely source of the limestone clasts. Sr isotope dates of about 22 Ma for both the Otorohanga Limestone and Papakura Limestone clasts are further supportive of this link. Trace element and stable oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotope data, not shown here but available on request, show little variation between the two limestones also. Fig. 6 represents a paragenetic sequence of geologic/diagenetic events determined for these rocks by integrating field, petrographic, stable oxygen and carbon isotope data while Fig. 7 provides a simplified burial history plot. Events are briefly discussed below.

Event 1 - Otorohanga Limestone deposition (Fig. 6,7)

A change from siliciclastic-rich shelf sedimentation of the massive calcareous Waitakian-aged to carbonate-dominated sedimentation of the Otorohanga Limestone occurred in the Waitakian Stage and probably marked the maximum extent of marine transgression and the disappearance of any significant substantially exposed land mass. A virtually non-existent siliciclastic supply allowed for the establishment and proliferation of carbonate factories on a cool-water, mid- to inner-shelf setting producing pure and coarse skeletal carbonates (Figs. 4A,B and 6). Skeletons were worked to form subaqueous dunes which migrated under the influence of strong tidal currents (e.g. Anastas et al. 1997, 1998) to produce large scale cross-bedded carbonate deposits (Fig. 3A). Locally important aragonitic skeletal populations (Fig. 5C) made for a carbonate deposit with high digenetic potential (e.g. Hood and Nelson 1996). Water depths increased with time to more open-oceanic conditions reaching mid-shelf water depths of >80 m (e.g. Dix and Nelson 2004) in the later Waitakian resulting in the disappearance of calcareous red algae, increased proliferation of bryozoan colonies, the sudden appearance of planktic foraminifera tests *(Globigerina* sp.), and progressively finer, more tightly packed carbonate material.

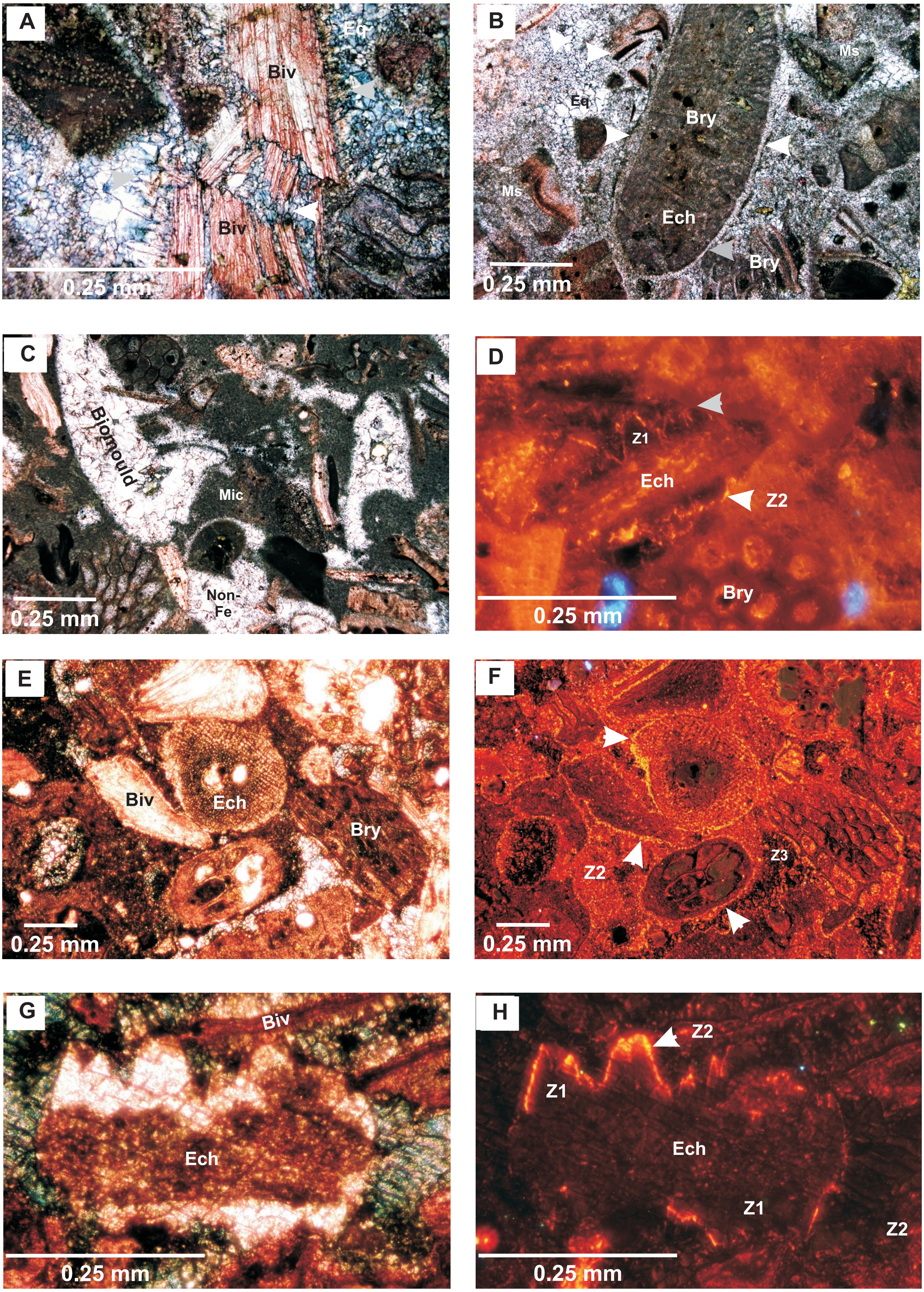
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Fig. 5: *(facing page) Photomicrographs showing key diagenetic features of representative stained thin sections of Otorohanga Limestone* **(A** *to* **D)***, Te Kuiti Group, and Papakura Limestone clasts* **(E-H)***, basal Waitemata Group as seen under plane-polarised light (PPL) or cathodoluminesence light (CL).* **(A)** *Non-ferroan (pink stain), bladed to fibrous marine cement coating a bivalve fragment. Both the bivalve host (white arrowhead) and fringing cement (grey arrowheads) have been fractured during later physical compaction associated with burial. Fracture- and remaining pore-fill is provided by pressure dissolution derived ferroan (blue stained) (micro)equant calcite, PPL.* **(B)** *Coarse crystals of dominantly non-ferroan equant calcite infilling biomoulds created by the dissolution of aragonitic bivalves. Aragonite retention initially into the burial realm was possible due to the protection provided by the micrite before dissolution and cementation occurred, PPL.* **(C)** *Open fabriced pure bryozoan-dominated poorly washed grainstone. White arrowheads indicate dirty, inclusion-rich, non-ferroan, generally isopachous fringing marine cements. Evidence of later pressure dissolution of fringe cements is shown (grey arrowhead). Most original intergranular micrite has recrystallised to non-ferroan to ferroan microspar, PPL.* **(D)** *Echinoderm fragment with moderately asymmetrically developed spired syntaxial rim cement exhibiting a initially non- (Z1) then thin bright-luminescent zonation (Z2). Pressure dissolution during later burial has truncated (grey arrowhead) these early formed (white arrowhead) zones, CL.* **(E)** *Thin non-host specific non-ferroan fringing marine cements occurring within both an inter- and intra-skeletal porosity showing in* **(F)** *a patchy dull to moderately bright CL (white arrowheads). Intergranular pore volume is occluded by very dirty non-ferroan and dull-luminescent microspar (Z2), aggraded from micrite, and clean dominantly non-luminescent ferroan sparry equant calcite (Z3).* **(G)** *Echinoderm fragment with a non-ferroan spired syntaxial rim growth which appears in* **(H)** *as a thick non-luminescent Z1 followed by a thin bright Z2. Note pore occluding ferroan non-luminescent microequant calcite derived from pressure dissolution. Bivalves (upper right) display a non-luminescent bladed fringing marine cement. Biv, Bivalve; Bry, Bryozoan; Ech, echinoderm; Eq, equant (pore occluding); Fe, Ferroan; Mic, micrite; Ms, microspar.*

Event 2 – Otorohanga Limestone partial lithification (Fig. 6,7)

Early lithification of the Otorohanga Limestone bioclastic material was initiated in localised areas nearest shore. First formed fringe cements, including syntaxial rim cements, were precipitated from relatively warm, high-energy, oxidised and carbonate-enriched shallow shelfal waters in the marine phreatic environment, at or just below the seafloor (Fig. 5A-H) (e.g. Dodd and Nelson 1998). Localised pore supersaturation with respect to carbonate was achieved by the dissolution of localised beds of aragonitic bivalves. Together these early very shallow formed cements may have resulted in localised firmground development (e.g. Nelson et al. 1988) to the east of Gibsons Beach. Locally micrite of mainly microbioclastic origin (some may be a true marine precipitate/cement) infiltrated or was pumped within some facies (Fig. 5B,C) enabling some aragonite preservation into the burial realm (Fig. 4C). Biomoulds may further indicate localised softground formation (e.g. Nelson and James 2000).

We infer that diagenesis continued further into the burial diagenetic realm occurring prior to Events 3 and 4. This would have necessitated the need for sediment accumulation atop the Otorohanga Limestone beyond the few m that have survived erosion to be preserved in the rock record today. To the south of Gibsons Beach, in the vicinity of Waitomo, the Otorohanga can reach thicknesses in excess of 60 m (Nelson 1978). Even if pre-erosional thicknesses at Gibsons Beach, and inland of Gibsons Beach had been substantially more than is evidenced, then further shallow-burial diagenesis would have been possible through burial by the upper Otorohanga Limestone deposits themselves. With burial in the order of only a few tens of metres (e.g. Dodd and Nelson 1998), early but minor pressure dissolution cementation may have been initiated thus providing a better lithified limestone than was possible through near-seafloor/very shallow burial cementation alone.

Event 3 – Otorohanga Lst cannibalisation, Papakura Lst deposition (Fig. 6,7)

Following partial lithification the Otorohanga Limestone experienced uplift and inversion during the earliest Miocene (middle and late Waitakian, e.g. Hayward 1993). Uplift was accompanied by tilting and fracturing producing what is envisaged to have been a subaerially-exposed fault scarp of Otorohanga Limestone adjacent to a high-energy shallow-marine environment floored also by partially indurated Otorohanga Limestone. Physical erosion of the nearby subaerially exposed Otorohanga Limestone was in the order of up to tens of metres, whilst much further inland, more wide-spread erosion of up to hundreds of metres completely removed the late Eocene to Oligocene Te Kuiti Group in some areas across this differentially tilted fault block (e.g. Kear 1963; Dix and Nelson 2004). Uplift may be explained by the initial phases of propagation of the modern plate boundary through New Zealand. This appears synchronous with that occurring further south along the eastern margin of Taranaki Basin, exposing major siliciclastic source areas to erosion that thereby extinguished carbonate

Event	Description	Tectonics	Environment/ conditions/timing	Key processes
1	**Deposition of Otorohanga Lst**	Burial	•Siliciclastic-free → clear waters •Inner- to mid-shelf waters •Tidally/storm swept •> 8°C seafloor •~20°C sea surface •Oxidising •Lw (~22 Ma)	•Deposition of pure (to 98% CaCO3) shallow-shelf skeletal grainstones to rarer packstones •Reworking of skeletal sands •Carbonate dune migration → tabular cross-bedding Seas transgressed during deposition
2	**Partial lithification of Otorohanga Lst**		•Seafloor to shallow-burial (few 10s m) •> 8°C seafloor, ~20°C sea surface •Normal marine porefluids •Oxidising to mildly reducing •Increasing temp/pressure with burial •<22 Ma to > 21.7 Ma	•Aragonite dissolution → localised supersaturation → marine modified porefluids •Marine → shallow burial fringe cements/syntaxial rim cements/(micro)equant - nonferroan, dull to bright CL •Infiltration/pumping micrite •Burial → physical/chemical compaction •Cementation → lithification → physical competency
3	**Erosion/ cannibalisation of Otorohanga Lst**		•Surface/subaerial temperatures and pressures •Meteoric fluids •Oxidising •>21.7 Ma	•Rapid inversion → differential uplift → fault scarp in Otorohanga Lst •Physical erosion → cannibalisation → accumulation (sub)rounded, pitted clasts in proximal shoreline position •Meteoric exposure → chemical weathering → pitted clasts •Offshore → swell waves → smooth-undulating, locally channelised erosion surface •Localised exposure/erosion underlying Waitomo Sst
	Mass deposition Papakura Lst conglomerate	Uplift, tilting of fault block	•Inner-shelf → <50 m •Steep shore platform •Sea bottom temps/pressures •Po <21.7 Ma	•Debris flows → westwards → beds pebble/cobble lst clasts •Triggers → seismic, storms → episodic events •Emplaced into coeval mixed siliciclastic-carbonate sediments •Lensoidal beds → channel/erosion surface fill
4	**Burial cementation – Otorohanga and Papakura Lsts**		•Shallow → deep burial •Increasing temps/pressures •av. 23 - 26°C •Up to 0.9 km burial •Oxidising to strongly reducing •Normal → connate/modified fluids •>21.7 Ma	•Rapid sedimentation → Waitemata Gp siliciclastics/flysch •Rapid burial → pressure dissolution, fitted tight fabrics •Papakura - minor fringe cements •Pore filling $\delta^{18}O$ depleted, dull CL, Fe-rich (to 14,000 ppm), low-Mg (micro)equant calcite cements •Interpenetrating limestone clast contacts
5	**Uplift and modern-day exposure**		•Inversion Late Pliocene/Pleistocene •Strongly reducing → oxidising •Decreasing temps/pressures •Surface conditions	•Exhumation and erosion during Late Miocene-Recent •Uplift, westward tilting, erosion of overburden → coastal exposure

Fig. 6: *Event model summarising the interpreted sequence of paragenetic events detailed by the Otorohanga Limestone, Te Kuiti Group, and Papakura Limestone, basal Waitemata Group, Gibsons Beach, eastern Taranaki Basin margin. NZ stages - Lw, Waitakian; Po, Otaian.*

accumulation in Taranaki and onland King Country Basins, and more regionally. This correlates with the placement of the overthrust basement into Taranaki Basin occurring between 23.8 (mid Waitakian) and 19 Ma (Otaian/Altonian) (Kamp et al. 2004).

Offshore the largely unlithified Otorohanga Limestone underwent erosion and modification by swell waves sweeping the shallow-shelf resulting in a smooth and broadly undulating and locally channelised erosion surface (Fig. 3B). Nearshore, rapid physical erosion and mass wasting of the limestone scarp, situated east of the modern Gibsons Beach, generated a nearshore accumulation of Otorohanga Limestone rubble deposits which were meteorically exposed to produce a pitted/weathered exterior surface (Fig. 3F). The lithified carbonate clasts were worked for a period in a near-shore high energy environment before being periodically mass-emplaced forming bedded often channelised limestone-in-limestone deposits

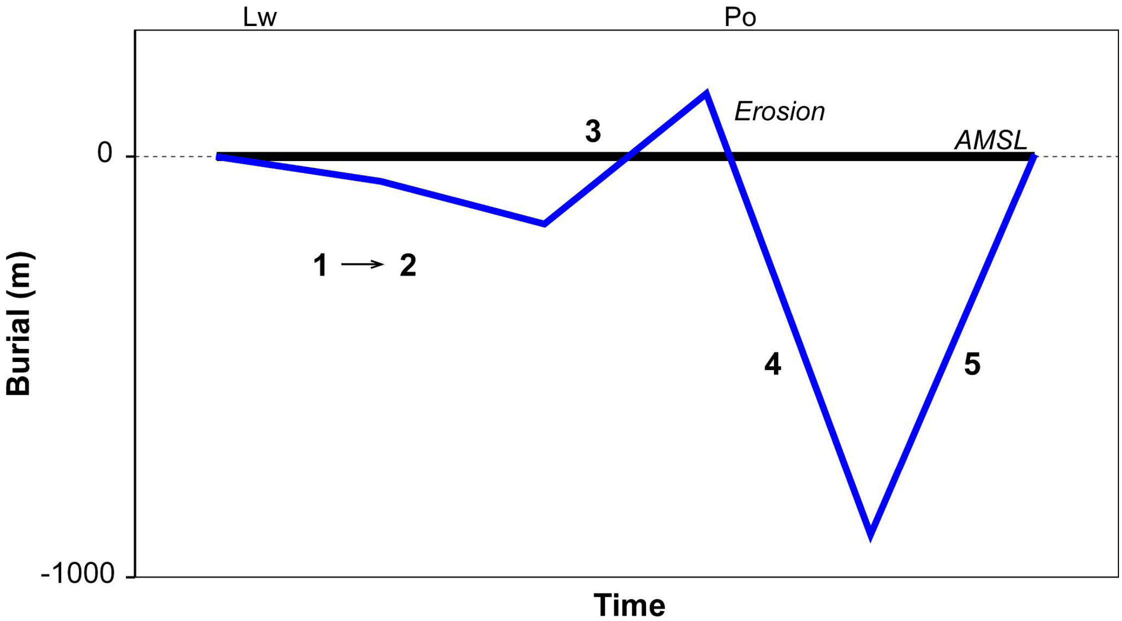

Fig. 7: *Schematic burial history plot for the Otorohanga Limestone, Gibsons Beach. Not to scale. Lw, Waitakian; Po, Otaian.*

(Fig. 3B-E). Mass debris flows occurred westwards triggered by episodic storm and/or seismic events and flowed short distances offshore to be deposited across the bordering shelf margin which was accumulating coeval carbonate deposits. Coeval skeletal material from the contemporary paleoshelf became smashed during mass-emplacement to form the coarse-grained skeletal hash matrix infilling between the clasts of Otorohanga Limestone (Fig. 3F).

Event 4 –Otorohanga and Papakura Limestone burial cementation (Fig. 6,7)

The Papakura and Otorohanga limestones were buried by the siliciclastic-rich Waitemata Sandstone and later turbiditic depositional sequences. Subsidence to bathyal depths is thought to have occurred in <1 million years (Ricketts 1989). Earlier formed fringe and syntaxial rim cements within the Otorohanga parent and parent-derived clasts partially succumbed to increasing burial and pressure dissolution effects (Fig. 5A,D). The final precipitates where pore-filling burial-induced pressure dissolution derived equant cements formed from carbonate-enriched porefluids in strongly reducing conditions (Fig. 4C,E; 5A,G) (e.g. Hood and Nelson 1996, Hood et al. 2003b,c). Any non-ferroan equant calcite was formed in the burial reducing environment but in the absence of siliciclastics to provide an iron source (Fig. 4A).

$\delta^{18}O$ values show pore-filling cements in the Otorohanga Limestone precipitated at minimum paleotemperatures of 19-29 °C (av. 25°C) corresponding to minimum paleoburial depths of ~400 to > 700m (av. 600 m) (Fig. 6, Table 3). These values are inline with other values reported for Te Kuiti Group limestones (e.g. Nelson et al 1988, 1994). $\delta^{18}O$ values from reworked Otorohanga Limestone clasts within the Papakura Limestone yield similar paleotemperatures of 19-25 °C (av. 23°C) and paleodepths of ~400 to >600 m (av. ~500 m). These burial depths on average indicate overall cementation depths of c. 100 m shallower than in the Otorohanga Limestone and may reflect the effect of earlier formed marine and shallow-burial cements (Fig. 5A-F). These burial depths suggested by isotopic evidence are supported by petrography. Grains commonly display concavo-convex contacts and only rarely microstylolitic contacts. Microstylolitic contacts are reported to not develop until burial depths of c. >700 m (e.g. Nicolaides and Wallace 1997). Pore occlusion was by pressure dissolution derived ferroan calcite (Fig. 4G,H).

Petrographic evidence obtained from the contact between the limestone clasts and the matrix does not show any obvious skeletal fracture or breakage supportive of the integrity of the limestone clasts at the time of deposition. Similar conclusions can be reached in outcrop where clasts are intact and in no way appear deformed (Fig. 3D). What is apparent however is often fitted concavo-convex pressure dissolved contacts between clasts suggestive again of competency during burial (Fig. 3E).

The mixed siliciclastic-shell matrix of the Papakura Limestone appears to have been relatively aragonitic poor, as evidenced by few aragonitic biomoulds and little fringe cementation. Syntaxial rim cements were not at all well developed. (Fig. 4G). $\delta^{18}O$ values from the limestone matrix in the Papakura Limestone provide the most depleted values which translate into paleotemperatures and paleodepths of 22-34°C (av. 26°C) and 500-900 m (av. ~600 m) respectively (Fig. 6, Table 3). These burial depths indicate that in the vicinity of Gibsons Beach, at least 900 m of Waitemata Group must have been deposited to achieve these burial depths.

Event 5 – Otorohanga and Papakura Limestone uplift and exposure (Fig. 6,7)

Inversion of the Gibsons Beach area occurred in the latter part of the Early Miocene (Hayward 1993) as part of wider eastern Taranaki Basin margin uplift resulting from crustal shortening. Uplift in the Gibsons Beach area, westward tilting and erosion has exposed the youngest Te Kuiti Group sediments, the Otorohanga Limestone and the oldest Waitemata Group sediments, the Papakura Limestone, Kawau Subgroup.

Concluding remarks

The paragenetic sequence of events documented at Gibsons beach (Fig. 6), including the cannibalisation of eastern Taranaki Basin margin deposits during Late Oligocene to Early Miocene times, must be attributed to active inversion/uplift, fracturing, and subaerial erosion of a local depocentre along the eastern Taranaki Basin margin before being buried to depths of at least 1 km by Waitemata Group sedimentation (Fig. 7). The driving tectonic forces behind these tectonic oscillations occurring during this restricted Oligocene to Early Miocene timetable were related to the propagation of the modern Pacific/Australian Plate boundary through New Zealand and the effects of westwards basement overthrusting from the east along the Taranaki Fault Zone.

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