Neogene Plate Tectonic Reconstructions and Geodynamics of North Island Sedimentary Basins: Implications for the Petroleum Systems

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Abstract

Although the modern Australia-Pacific plate boundary through New Zealand is relatively straight, there have been significant changes in its geometry during the Neogene. Within the North Island sector there has been a fundamental transition from an Alpine Fault translation/transpression regime to a Hikurangi margin subduction regime. This transition has been accompanied by the southward encroachment of the edge of the Pacific plate oceanic slab into Australia lithosphere, shortened and thickened along its eastern margin as a consequence of the prior Alpine Fault transpression, the process now operating in South Island. The response of the Australia lithosphere at the surface to the emplacement of the subducted slab at depth, has differed in the East Coast forearc region versus the foreland in western North Island, where the depth to the slab is greater and there has been a characteristic southward migration of depocentres pinned to the leading edge of the slab. The recent publication of new rotation parameters for relative motion of the Australia, Antarctic and Pacific plates, have provided key new data from which to plot the successive emplacement history of the Pacific slab beneath North Island, thus enabling the comparisons to be made with basin stratigraphy and geohistory. These data also constrain the age of subduction initiation at various points along the present trend of the Hikurangi Trough, identifying a younging of subduction initiation to the southwest. An implication of this younging direction is that the modern accretionary prism south of Cape Kidnappers can be no older than late Miocene (c. 11 Ma). The focus of this paper is on new ideas about the tectonic development of North Island and its basins, which have implications for hydrocarbon exploration.

1. Introduction

Publication by Cande and Stock (2004) of revised Cenozoic parameters for relative motion of the Australia, Antarctic, and Pacific plates make it timely to reconsider the 3-D geometry of the Australia-Pacific plate boundary zone through New Zealand, and how the lithosphere has responded through the Neogene to changes in geometry and plate interactions, thereby forming and deforming sedimentary basins. The much reduced magnitude of uncertainties associated with the Cande and Stock (2004) finite rotations suggest that, at the scale of plates, the kinematic framework is more-or-less settled for the New Zealand sector of the Australia–Pacific plate boundary. This means that for the first time we can reliably calculate the positions through time of the leading (southwest) edge of the subducted slab of Pacific plate relative to overriding Australia plate in North Island and northernmost South Island. For these types of calculations to be meaningful, we first need to know where the leading edge of the slab at mantle depths is currently located, and where it projects to the surface on the Australia plate. In relation to the transpressive part of the plate boundary zone in Marlborough, a key question is whether or not, and if so, how, Australia plate may be capturing blocks of Pacific plate crust.

In this paper we present, as work in progress, new thinking about how the lithosphere in North Island, which carries oil-prone sedimentary basins, has responded to changes in plate interactions. We start with the presentation of new tectonic reconstructions based on the rotation parameters of Cande and Stock (2004), including the position of the slab edge through time, which leads on to the question of the present transition geometry between the Hikurangi margin and the Alpine Fault transpression zone. We then briefly outline key observations about the Neogene geological evolution of North Island that have a bearing on lithospheric processes and how basin formation is spatially and temporally related to the advancing position of the slab edge. We then outline a new conceptual model/working hypothesis of how the advancing Pacific slab may be creating space by driving delamination of the lower lithosphere from upper lithosphere in the Australia plate. The sinking of the delaminated lithosphere potentially drives the pattern of subsidence and subsequent uplift, observed for basins in western and central North Island. We then consider implications of the tectonic reconstructions for the timing of subduction initiation along eastern North Island, and for the spatial versus temporal replacement of strike-slip deformation by subduction accretion along the margin.

2. Tectonic setting and reconstructions

Fig. 1 gives a simplified view of the Australia-Pacific plate boundary zone through New Zealand. The Alpine Fault segment links in a southwest direction with the Puysegur subduction zone. To the northeast the Alpine Fault links diffusely with the Hikurangi margin subduction zone. The current direction and magnitude of relative Australia-Pacific motion (from DeMets et al., 1994) is oblique to the structural trench where the oceanic plate is subducted. The approximate position of the leading edge of the subducted Pacific plate beneath northern South Island projected to the surface, but not unfolded, is shown as a broken line. The position and orientation of the subduction zone at about 23 Ma, when relative motion on a through-going Australia-Pacific plate boundary started (Kamp, 1986; King 2000), is constrained to have lain along the base of the continental slope east of northern North Island, as approximately shown in Fig. 1, although there is no longer bathymetric evidence for a trench. This margin was co-linear with the northern edge of the Chatham Rise prior to its displacement due to relative plate motion through New Zealand.

The distance between the 23 Ma paleo trench position and the present location of the leading edge of the subducted Pacific slab is about 500 km, which is nearly identical to the offset on the Alpine Fault in South Island. Also shown on Fig. 1 are small circles for the plate motion scheme of Cande and Stock (2004) for 2.6 Ma to present, and 10.9 to 2.6 Ma, both pinned at the southern end of the Alpine Fault (Milford Sound), which support the reconstructions in Fig. 2. Key differences between the Cande and Stock (2004) rotation parameters, versus earlier determinations (e.g. Stock and Molnar 1987, Cande et al. 1995), is that much less convergence normal to the plate boundary (Alpine Fault) can be inferred for the Neogene, and the marked increase in convergence across the boundary thought to have occurred around 6.4 Ma in prior studies is an artefact of the earlier data.

The small circles shown in Fig. 1 approximate the position of the plate boundary in the upper mantle at different stages. Clearly, the 2.6 Ma to present small circle, northward from Milford Sound to Cook Strait, increasingly diverges from the Alpine Fault. What may have happened in the narrow triangle zone within the Southern Alps is that the plate boundary at upper mantle depths (lower lithosphere) progressively adjusted its position to be more easterly in response to changes in the plate motion vector, and consequently the Australia plate has captured Pacific plate lower lithosphere. The crust of the "Pacific plate" in the triangle zone is also being captured by the Australia plate, as reflected in the sequential formation to the southeast of the Marlborough faults, which have played a role in this capture process. We have traditionally regarded the plate boundary at the surface as lying along the Alpine Fault, but the northern section of this fault is no longer taking up all the plate motion.

Fig. 2 shows reconstructions for Australian and Pacific components of New Zealand at 20, 11, and 6 Ma using the euler poles of Cande and Stock (2004). The small circles for the Cande and Stock (2004) plate motion scheme (Fig.1) are shown as broken black curved lines in the respective maps. We also show on the 20 Ma reconstruction an estimate of the 23 Ma position of the paleo trench considered to have lain along the base of the continental slope of northern North Island. Several points emerge from these reconstructions.

(i) At c. 23 Ma the proto Alpine Fault must have linked to the southern end of the paleo trench, thereby forming a new Australia-Pacific plate boundary zone through continental New Zealand that could discretely take up relative plate motion. The strike of the northern end of the Alpine Fault at this initial stage may have diverged from the small circle describing the contemporary relative Australia-Pacific motion calculated from the appropriate Euler pole (Fig. 2). The amount of divergence from the small circle, which is related to the high angle intersection of the Alpine Fault with the paleo trench, determines the extent to which crust in Wellington-Wairarapa and the "undetermined" continental crust, belonged initially to Australia versus Pacific plate. The initial location of the intersection point must have lain north of the 20 Ma reconstructed position of the Marlborough block (red in Fig. 2), but its exact position is unknown.

(ii) During the Neogene the leading edge of the subducted Pacific plate oceanic slab, as unfolded to horizontal, was progressively emplaced to the southwest parallel to the plate boundary zone (see below section 3: "Backtracking of Pacific slab edge"). Moreover, the rate of emplacement of the slab parallel to the plate boundary was the same as the rate of

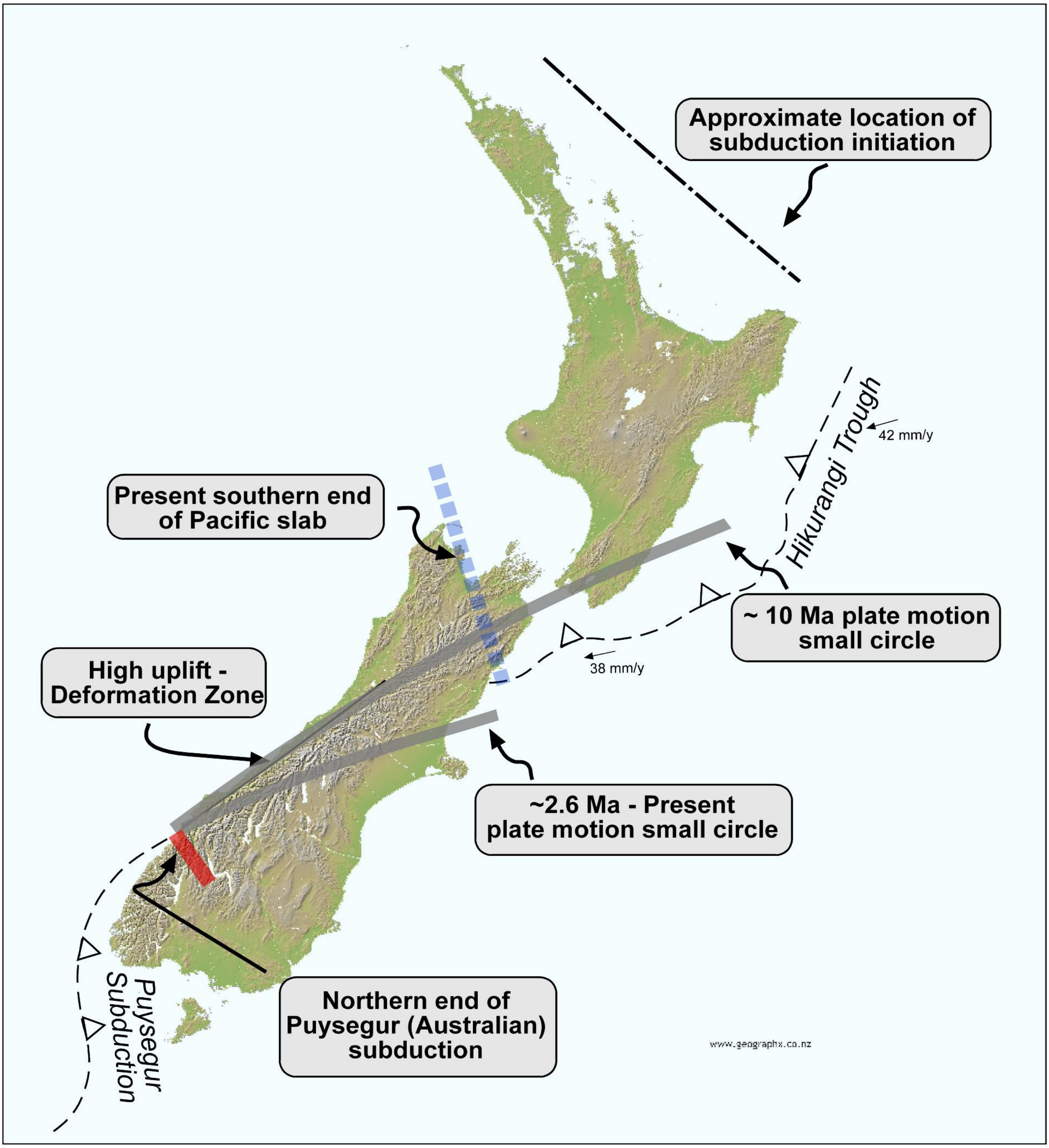

Figure. 1: *Synoptic map of New Zealand showing the main elements of the modern Australia-Pacific plate boundary through New Zealand. The plate motion small circles are calculated from Euler poles from the data in Cande and Stock (2004). The southern extent of the subducted oceanic Pacific plate adopted here is shown by the broken blue line extending from Kaikoura at the southern end of the Hikurangi Trough to Nelson.*

displacement on the Alpine Fault in the continental transpression zone to the south, which is logical given that they are two parts of the same (Pacific) plate. As the Pacific slab was emplaced beneath North Island, there was substantial roll-back of the Kermadec Trench to its present position (Fig. 2). During the Early Miocene this was associated with seafloor spreading in the South Fiji Basin, and during the Late Miocene to Recent by seafloor spreading in the Harve Trough. During the Pleistocene there has been continental rifting in the Taupo Volcanic Zone at the southern end of the Harve Trough.

(iii) There is a large area of "undetermined" continental crust in the 20 Ma reconstruction (Fig. 2). Prior attempts at restoration of Mesozoic basement terranes

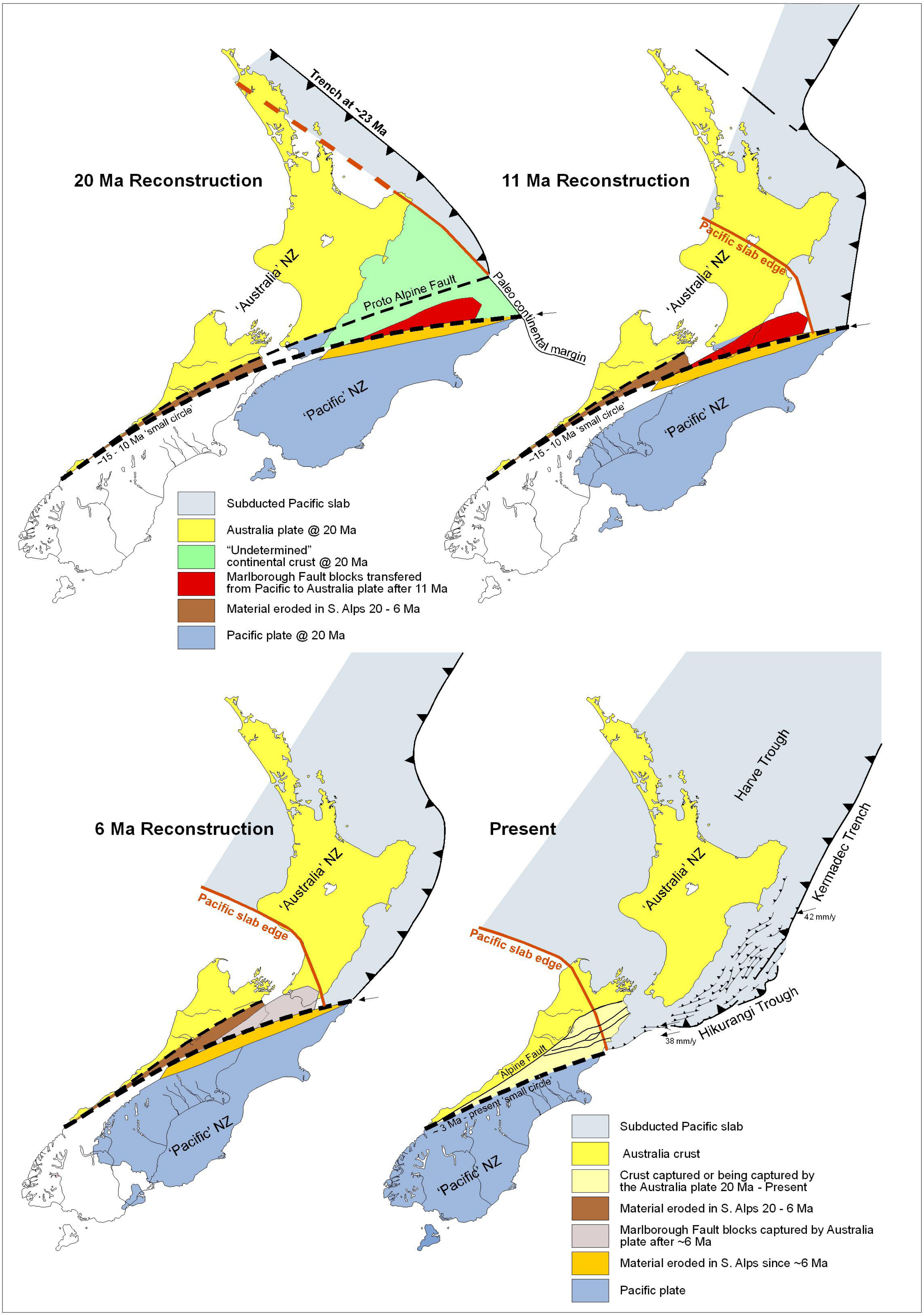
20 Ma Reconstruction
Trench at ~23 Ma
'Australia' NZ
Proto Alpine Fault
Paleo continental margin
'Pacific' NZ
~15 - 10 Ma 'small circle'
Subducted Pacific slab
Australia plate @ 20 Ma
"Undetermined" continental crust @ 20 Ma
Marlborough Fault blocks transfered from Pacific to Australia plate after 11 Ma
Material eroded in S. Alps 20 - 6 Ma
Pacific plate @ 20 Ma
11 Ma Reconstruction
Pacific slab edge
'Australia' NZ
'Pacific' NZ
~15 - 10 Ma 'small circle'
6 Ma Reconstruction
Pacific slab edge
'Australia' NZ
'Pacific' NZ
Present
Harve Trough
Kermadec Trench
'Australia' NZ
42 mm/y
Pacific slab edge
Hikurangi Trough
38 mm/y
Alpine Fault
~3 Ma - present 'small circle'
'Pacific' NZ
Subducted Pacific slab
Australia crust
Crust captured or being captured by the Australia plate 20 Ma - Present
Material eroded in S. Alps 20 - 6 Ma
Marlborough Fault blocks captured by Australia plate after ~6 Ma
Material eroded in S. Alps since ~6 Ma
Pacific plate

Figure. 2 (facing page): *Reconstructions for the Australia and Pacific plate components of New Zealand at 20, 11, and 6 Ma using the Euler poles of Cande and Stock (2004). Subduction started c. 23 Ma along the continental margin of northern North Island. The paleo trench linked to the northern end of the Alpine Fault transform. The northern end of the Alpine Fault transform is speculatively located within the zone of undetermined continental crust. The Hikurangi margin developed into the present configuration through emplacement of the oceanic Pacific slab into Australia lithosphere and lengthening of the Hikurangi Trough, concomitant with sea floor spreading in the Harve Trough. The heavy black lines show the small circles of relative plate motion for each reconstruction. See text for discussion.*

to an Early Miocene outline of continental New Zealand, as shown in Fig. 2, have tended to appeal to horizontal bending of these terranes to fill this space (e.g. Bradshaw et al., 1980; Kamp, 1987). In the reconstructions shown in Fig. 2, we have taken an alternative view that part of the space was occupied by discrete fault-bounded blocks that subsequently moved south westward relative to each other and undeformed Australia and Pacific crust on either side. Also, some of the 'undetermined" continental crust was eroded from the Pacific plate in the Southern Alps after about 20 Ma. Australia crust in the Marlborough Sounds block has probably been shortened and partly eroded and rotated clockwise during the Early to Middle Miocene. Basement (?Australia crust) in parts of Wellington and Wairarapa have also been shortened and transported to the southwest relative to undeformed Australia plate farther west. This may have occurred on discrete fault(s) that would represent abandoned northern (early) strand(s) of the Alpine Fault.

(iv) In Fig. 2 we have attempted to show qualitatively where continental crust eroded in the Southern Alps between c. 11 and 6 Ma, and after 6 Ma, may have been located at 20, 11 and 6 Ma, respectively. We also show reconstructions at 20, 11 and 6 Ma for the basement block of Marlborough between the Alpine Fault and Awatere Fault. The process by which Australia plate progressively captured Pacific plate crust, due to the more easterly orientation of the plate boundary at upper mantle depths through time, explains why the crust eroded after c.6 Ma in the Southern Alps reconstructs to a more north easterly position at c.20 Ma than the Marlborough fault block.

(v) No attempt has been made in the reconstructions shown in Fig. 2 to restore the 20 km or so displacement between the Fiordland block and basement in western Southland. Nor has obvious late Neogene east-west crustal shortening in northern Fiordland and west Otago been restored in the Early and Middle Miocene reconstructions. The curvature of the small circles suggest that it is unlikely that there has been more than 20 km or so relative plate motion along the Fiordland Boundary Fault between the Fiordland block and the Waiau Basin.

3. Backtracking of Pacific slab edge

From the Cande and Stock (2004) Euler poles we can backtrack to the paleo trench the leading edge of the Pacific slab to determine the timing of subduction initiation and the emplacement history of the slab (Fig. 3). The dashed line in red shows the surface projection of the slab edge, as inferred here (see section below on seismicity), that when unfolded to horizontal is given by the 0 Ma green line. The slab edge positions as indicated in Fig. 3 have all been unfolded for Benioff Zone dip to take them to the horizontal. The c.20 Ma position of the slab edge lies a short distance inboard of the continental margin along northeast North Island, but this would backtrack to that margin given the c.23 Ma age of the start of dextral motion on the modern Australia-Pacific plate boundary. The change in strike of the slab edge (e.g. along the 0 Ma line) may be inherited from the shape of the paleo continental margin. The intersection of the backtracked slab edge with the Hikurangi Trough determines the age of subduction initiation along the present location of the structural trench, which clearly gets younger from north to south in the current frame. These data establish the timing along the eastern margin of North Island when deformation driven by transpression was supplanted by subduction driven processes.

4. Definition of the southern edge of the Pacific slab – the seismicity picture

In the preceding section it was assumed that the dashed red line in Fig.3 represented the surface projection of the southern edge of the Pacific subducted slab. At the surface, the southern end of the oceanic Pacific plate cannot be further south than Kaikoura, which lies at the southern end of the Hikurangi Trough. At issue is whether the slab edge at upper mantle depths lies on a trend through Nelson, as assumed above, or more westerly, such as through Westport. Previous analyses of the seismicity in the region by Anderson and Webb (1994) and Eberhart-Phillips and Reyners (1997) have favoured the more westerly trend, which places a cluster of deep seismicity near Motueka (Fig. 3) as part of the Benioff Zone.

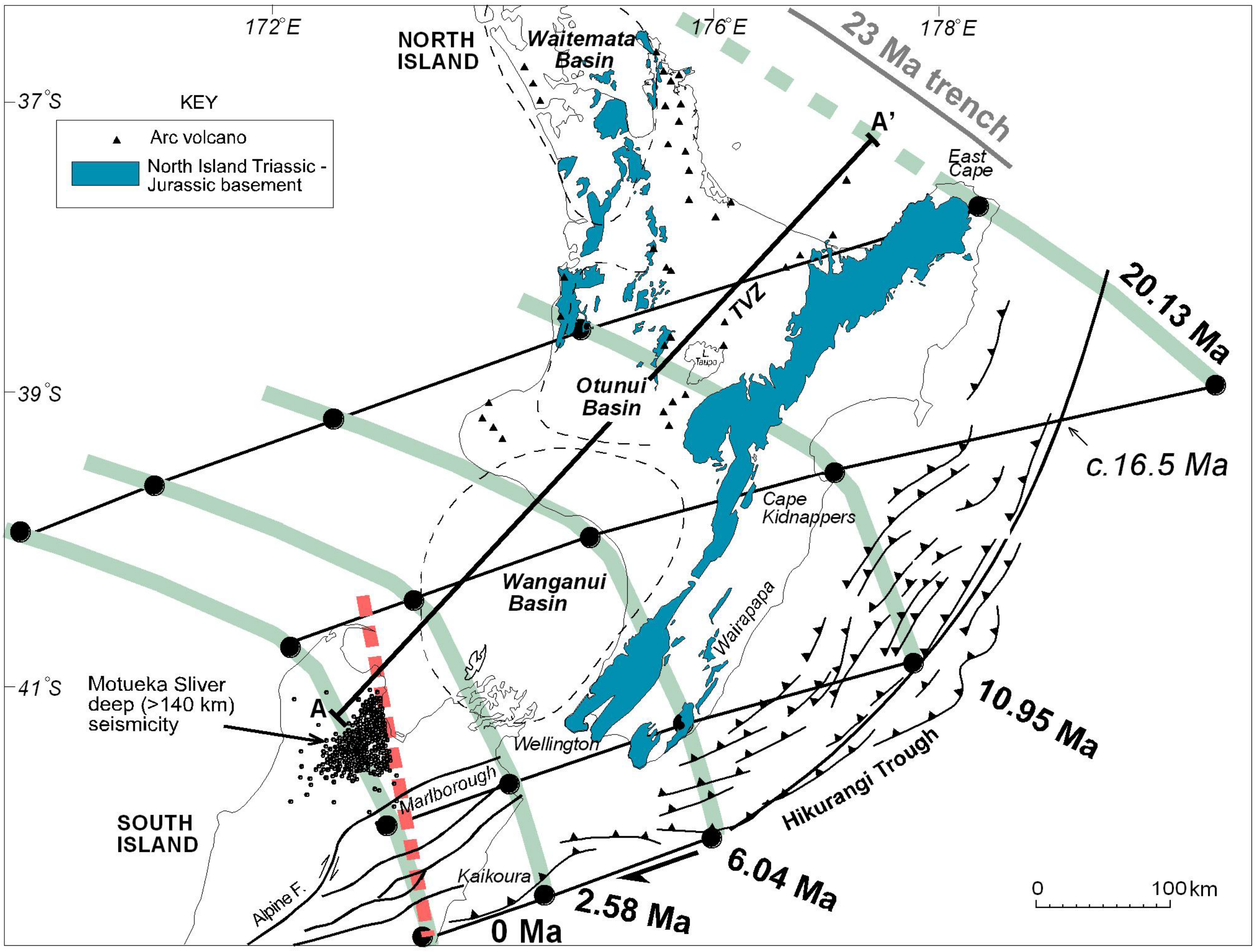

Figure. 3: *Reconstructions of the leading edge of the subducted Pacific slab relative to geological features on the surface of the Australia plate in the current reference frame. Red dashed broken line shows the surface projection of the slab edge that when unfolded to horizontal is given by the 0 Ma green line. That slab edge configuration is backtracked using Cande and Stock (2004) Euler poles to determine the maximum extent of the slab beneath North Island, and the southward migration of the southern termination of the trench given by the intersection of the present trench position with the slab edge. Location of the deep possibly non-Benioff zone seismicity labelled Motueka silver is shown southwest of the present slab edge.*

We have undertaken preliminary analysis of a seismicity dataset (New Zealand Geonet project: www.geonet.org.nz) including 101,345 events recorded during the period 01/01/1990 through 16/06/2003 of earthquakes ranging in magnitude from near zero to approximately 6.8, with an average magnitude of M= 2.3. Earthquake foci range from the surface to approximately 600 km, but more than 99.7% of them are shallower than 250 km, and 80% are shallower than 50 km. Previous studies have typically displayed the seismicity in profiles perpendicular to the trench, which can be misleading given the obliquity of the plate motion to the trench. We have analysed the data in a fully 3-D sense and present the interpretations in Fig. 4 as a series of profiles in the direction of relative plate motion, which reflects the trajectory of lithosphere through the subduction zone. As seen in Profile A (and typical of all profiles to the north), the Benioff Zone shows a typical subduction shape. In Profile C the Pacific slab is at shallow depths and the pattern of seismicity is complex and there is substantial variability in focal mechanisms in both the slab and the upper plate region (Reyners et al. 1997). In Profile B, and also in profile D (which is parallel to the strike of the Benioff Zone), the question is whether or not the deeper cylinder of seismicity from 90 to 250 km (Reyners and Robertson, 2004), which we have labelled Motueka Sliver, is part of the slab or spatially distinct. If this deeper seismicity is part of the subducted slab it would imply very marked curling over of its leading edge; unfolding this extended slab in the direction of plate motion and backtracking it to the trench, would require an additional 250 km of subduction and earlier subduction initiation by c.10 Ma than illustrated in Fig. 3. An alternative interpretation of the seismicity that requires further investigation is that the deep seismicity in Profiles B and D is linked to the overriding Australia plate, and is a sliver

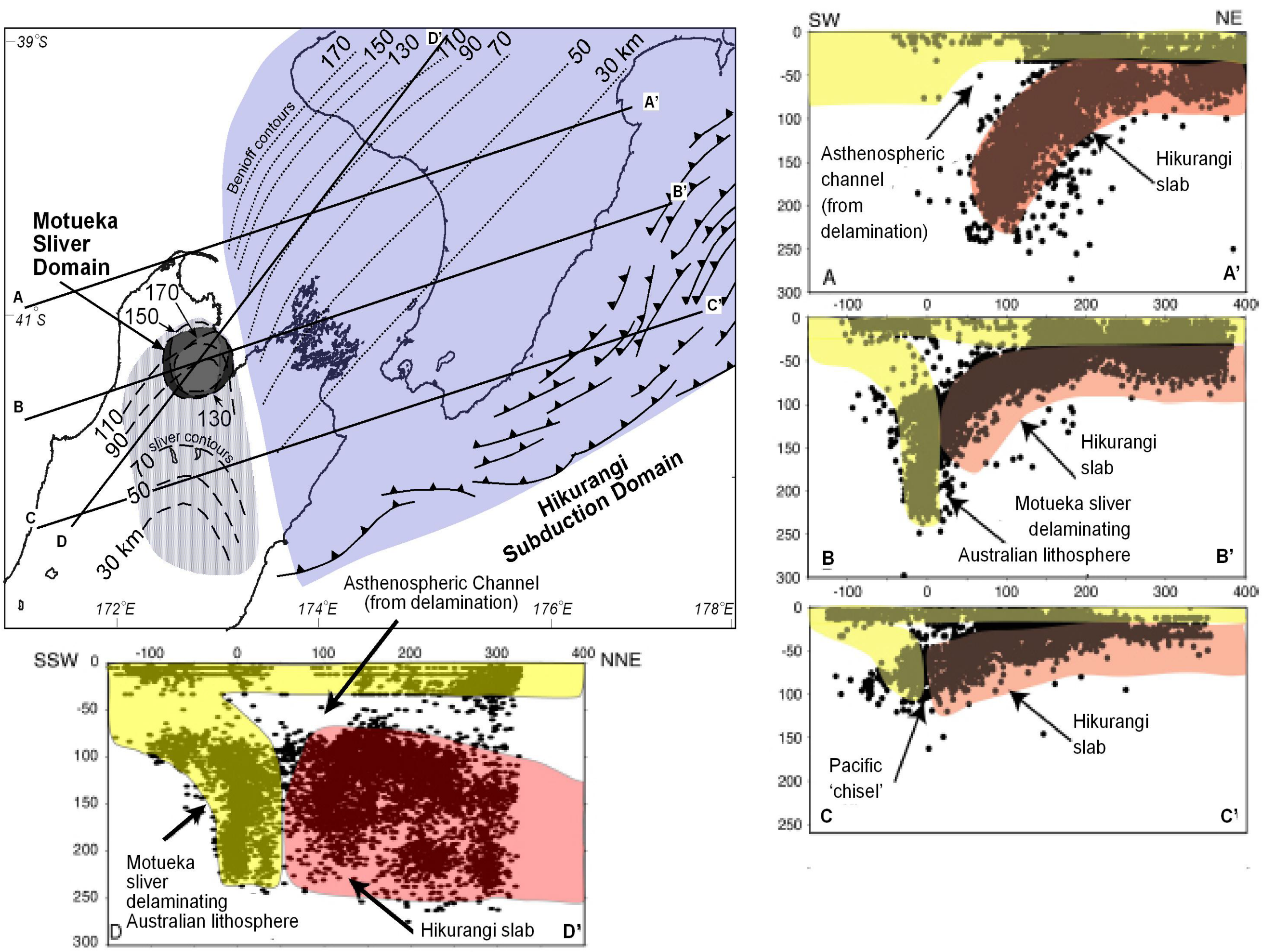

Figure. 4: *Interpretations of seismicity in the region of transition from South Island continental transpression to Hikurangi margin oblique subduction. Profiles A, B and C are in the direction of relative plate motion (i.e. particle motion down the subducted slab). Each profile is a projection of all seismicity within 10 km on each side of the profile. Motueka silver identified in profiles B and D shown here and analyses of seismicity in 3-D. Contours of the Benioff zone have been determined from Geonet seismicity data, as described in the text.*

of the Australian lithosphere that has been removed from the plate, possibly by the chisel-like action of the encroaching Pacific slab.

5. Geological observations of northern New Zealand

In this section we briefly outline geological observations, chiefly from western and central North Island, west of the forearc region, that represent signals as to how the surface of the lithosphere has responded during the Neogene to plate interactions at upper mantle depths.

The structural, geomorphologic, and volcanologic impacts of Hikurangi margin subduction on North Island are well known and have been emphasized in previous studies (Pettinga, 1982; Kamp, 1988, Lewis and Pettinga, 1993). Since the late Miocene an imbricate wedge and accretionary prism has formed beneath the shelf and slope offshore eastern North Island, the highest accretionary ridge and associated slope basins being exposed on land in hill country. A principal forearc basin lies further inboard in Hawke's Bay (Kamp et al., 1988). Taupo Volcanic Zone (TVZ) is the next major tectonic element to the northwest. It has produced numerous large-volume silicic eruptions during the Pleistocene, and contains andesitic volcanoes as well. The regions to the northwest of TVZ (Waikato and Auckland) exhibit Pliocene and Pleistocene back arc extensional basins and fields of basaltic alkaline volcanics.

Neogene geological features west of the forearc in Wanganui and King Country regions are not explicable in terms of shallow plate interactions. North-south through western North Island immediately west of Taranaki Fault there are a series of 100 km-wide middle Miocene to Recent sub-circular sedimentary basins (Otunui, Wanganui) (Kamp et al., 2004) that formed through flexural subsidence (Stern et al.,

1992) (Fig. 3). Originally the Otunui Basin and northern parts of Wanganui Basin may have extended across the area now occupied by TVZ and possibly merged with the Tununui Basin in eastern North Island (Kamp 1999). The modern marine depocentre occurs in the south involving Wanganui Bight, northern Cook Strait, and the drowned basement landscape of Marlborough Sounds in northernmost South Island. The basins subsided rapidly to bathyal depths and accumulated siliciclastic successions 2-3 km thick (see geohistory plots, Fig. 5). The basins have subsequently been sequentially inverted as broad flexural uplifts and concurrently variably eroded (Pulman and Stern, 2004; Kamp et al., 2004). This has given the formations east-west strike in northern Wanganui and King Country regions, which is at a high angle to the NE-SW structural grain in the forearc region. The degree of erosion increases to the north such that c.12-14 m.y after the basin formation, the lithosphere has been restored to its original elevation and the stratigraphic record of the basin has been almost completely removed by concurrent erosion. Another anomalous feature is that the southern end of recent andesitic arc volcanism (Mt Ruapehu) occurs some 3 degrees of latitude north of the southern end of the subducted slab.

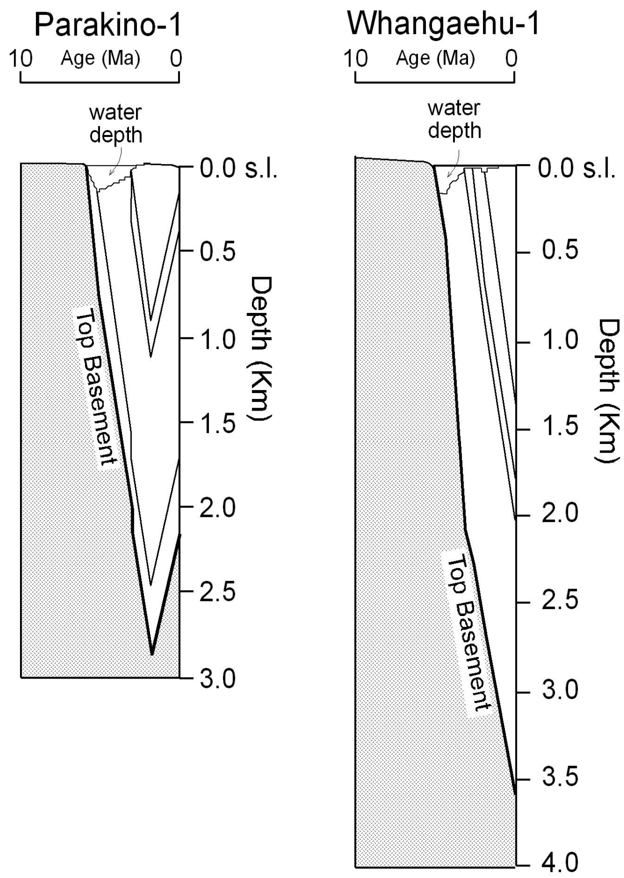

Figure. 5: *Geohistory plots for Whangehu-1 and Parakino-1 hydrocarbon exploration wells in Wanganui Basin,*

Cross-section A-A' (Figs 3, 6) through western New Zealand identifies the sequential migration of three fundamentally different phenomenon in concert with the southward emplacement of the leading edge of the Pacific slab into Australia lithosphere, as calculated from the Cande and Stock (2004) rotation parameters: (i) southward migration of crustal shortening in easternmost Australia plate forming part of the Alpine Fault transpressive regime, now located in South Island (Kamp et al, 1989; Tippett and Kamp 1993); (ii) southward migration of basin formation in the Australia plate; and (iii), southward migration of "arc" volcanism (Kamp, 1984; Hayward et al., 2001). These phenomena reflect for crust now in the southern part of the forearc region, southward migration of the transition from Alpine Fault continental transpressive tectonics to Hikurangi margin subduction tectonics; for the foreland to the west they reflect the response of the lithosphere to plate interactions at upper mantle depths. Something we do not fully understand at present is why prior to about 14 Ma the basin formation and andesitic volcanism in the Auckland and Northland areas appear to have preceded the emplacement of the slab (Fig. 6). This may partly reflect projection of Northland geology on to a cross-section (A-A') through central North Island, and possibly slightly earlier subduction initiation in Northland compared with East Cape, although there is little indication in Northland of subduction/obduction deformation until the mid Waitakian (23-24 Ma) (Isaac et al., 1994). Alternatively, the early Miocene rapid subsidence of Waitemata Basin may be due to crustal shortening accompanying the initiation of the subduction zone to the northeast, and plate interactions at shallow (crustal) depths during the first 100 km of subduction before positive buoyancy of the slab was overcome and a free-running system developed at c.14 Ma (Fig. 6). Although not considered before to our knowledge, melting giving rise to earliest Miocene volcanism in Northland may owe its origin to lateral disturbance of the upper mantle during the start of subduction to the east, and ahead of the appearance of the slab beneath the volcanoes.

6. Conceptual model

The observations described above lead us to propose a new model for the Neogene evolution of the lithosphere in North Island. There is a profound switch in plate interactions as the edge of the subducting Pacific slab migrates south-westward.

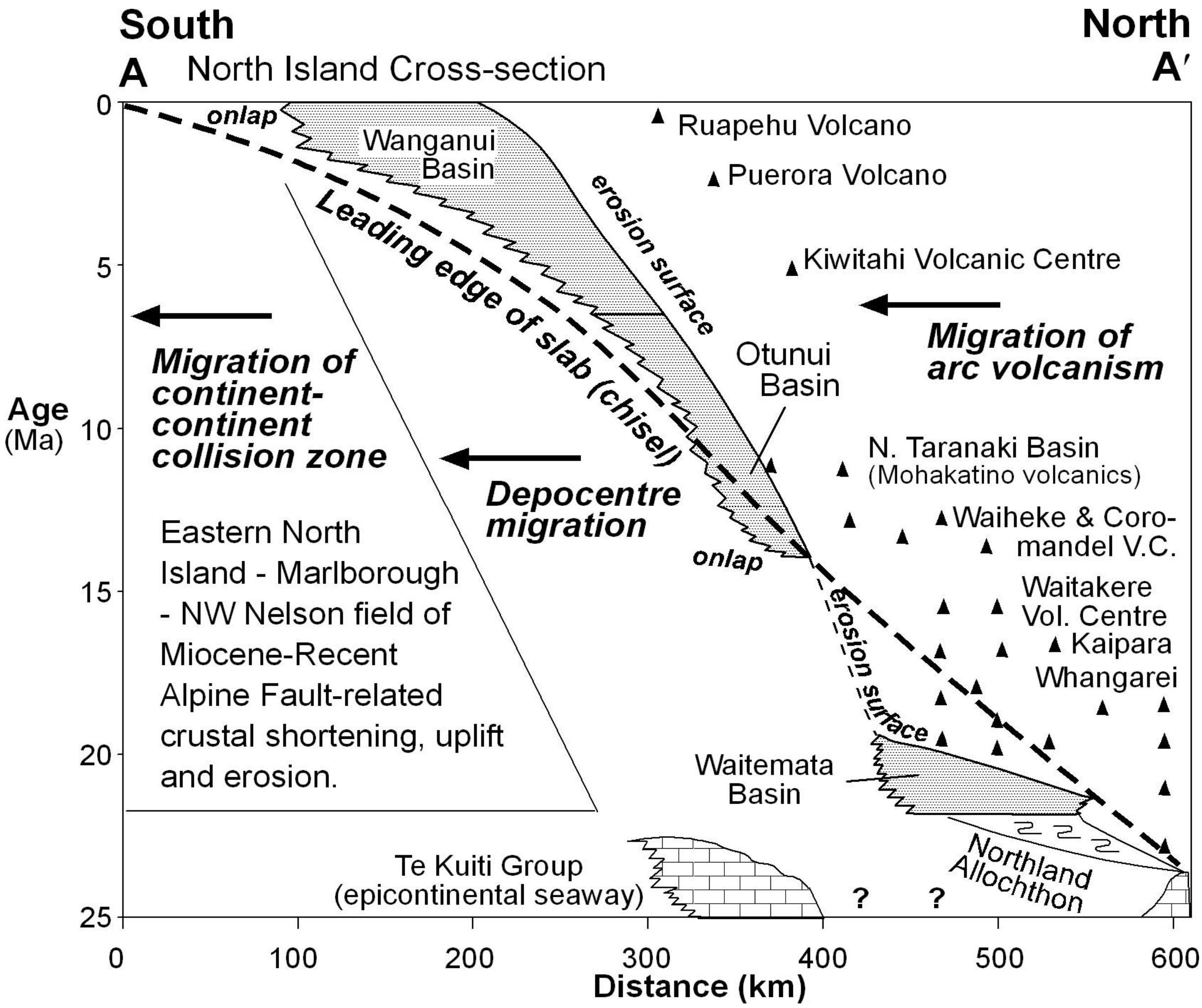

Figure. 6: *Time stratigraphic panel aligned parallel to the Hikurangi margin (profile A-A', Fig. 3) with elements of forearc, foreland, and back arc geology projected onto it. It illustrates the Neogene retreat to the south of the continental transpression as the Pacific crust progressively cleared eastern North Island, and the southward encroachment of the subducted Pacific slab closely associated with formation and migration of depocentres in the overriding Australia plate (Wanganui and Otunui Basins). The migration of these elements is followed by broad flexural basin inversion, and then eruption of arc volcanism. The accretionary prism is shown schematically and is difficult to illustrate on this section line. It is best developed in the southern part of the Hikurangi margin and its age at any latitude is younger than the formation age of the trench, which is closely related to the emplacement of the slab.*

Depending upon the location relative to the depth of the subducted slab edge, the tectonic interactions differ. We focus first on south eastern North Island and northernmost Marlborough, which currently lie in a forearc subduction zone, labelled the Pacific chisel in Fig.7. When this area was south of the slab edge, crustal shortening, uplift and erosion were driven by transpression in the Alpine Fault continent-continent collision zone. As the Pacific slab came beneath this region, it had to mechanically make space for itself. This resulted in additional crustal thickening, uplift and erosion driven essentially from below on a shallow subduction thrust, whereas the preceding continental transpression had had a more orthogonal shortening direction within the crust.

Northwest of the forearc (Pacific chisel) the depth of the slab/Australia interaction deepens. At approximately the 30 km depth contour the slab begins to drive delamination of the Australia plate crust from its upper mantle, resulting in the detached Motueka sliver as a near vertical seismically active feature, and in its wake to the north, a channel of thinned lithosphere. The crust-mantle rheologic boundary may at to localise the deformation. The tectonics in this zone reflects the interplay of the southward retreating Motueka sliver, and the asthenosphere that fills the resulting space. We propose, by analogy with lithospheric processes inferred for the Mendocino Triple Junction area in northern California (Furlong and Govers, 1999; Furlong et al., 2003; Furlong and Schwartz, 2004), that viscous coupling drives the basin-forming downwarp (Fig. 8). As the sliver continues to retreat to the south, driven by the chisel-like action of the Pacific slab,

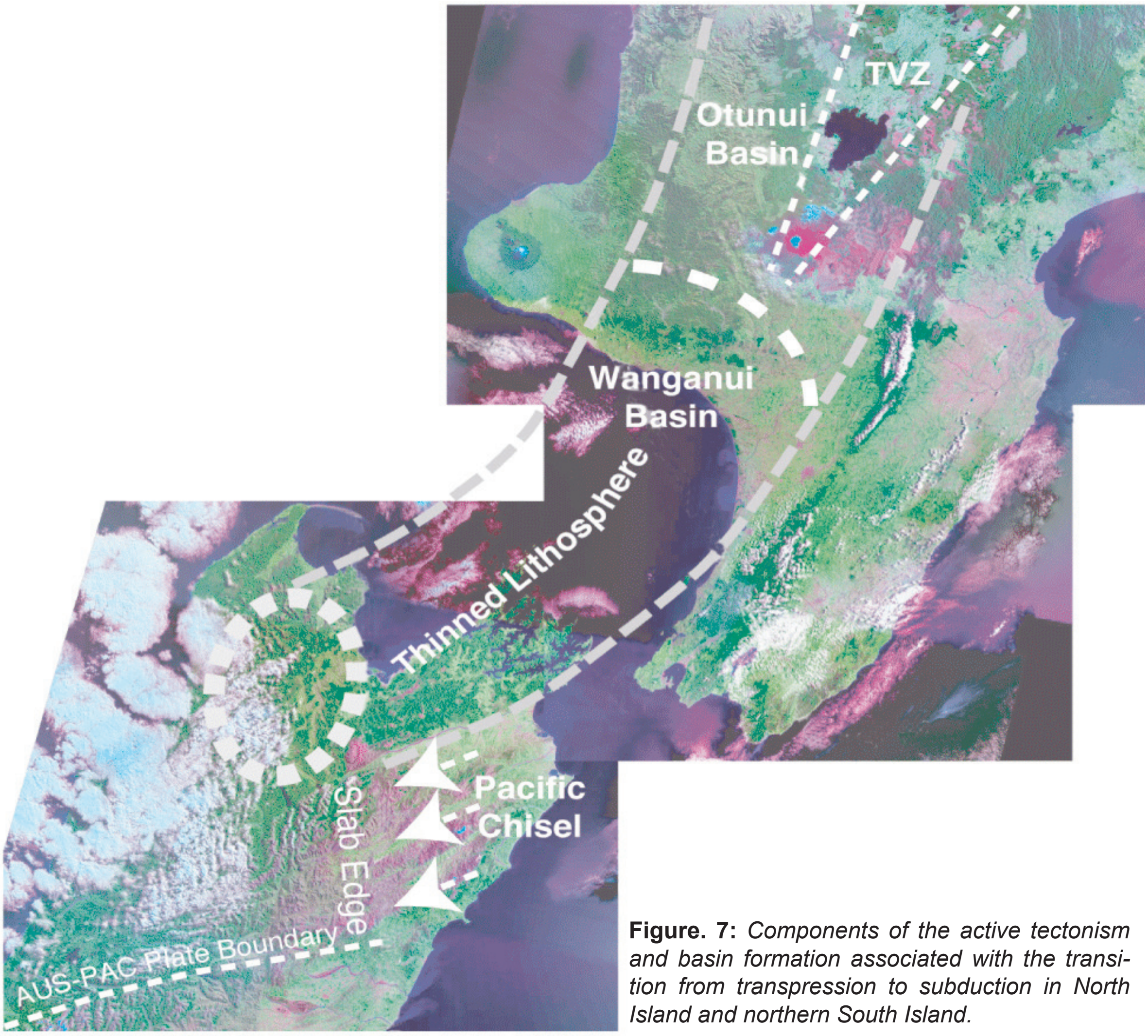

Figure. 7: *Components of the active tectonism and basin formation associated with the transition from transpression to subduction in North Island and northern South Island.*

the locus of maximum basin subsidence migrates in concert, producing the southward migration of basins in western North Island. Basin inversion is driven by thermal buoyancy when the forces associated with viscous drag have decayed. At depths greater than about 120 km any delamination of the lithosphere is too deep to have significant affects at the surface. The geological and geophysical data are in qualitative agreement with this model, and geodynamic processes are viable to drive the tectonics, but the model remains a hypothesis and the subject of continuing research.

7. Implications for hydrocarbon exploration in eastern North Island

The east coast of North Island is a frontier area for hydrocarbon exploration, and MED has been encouraging of exploration activity in this region, chiefly by the acquisition of extensive industry quality seismic reflection data offshore from East Cape and to the south of it. The last major conceptual advance in understanding about the tectonic origin of East Coast geology was made during the late 1970s and published during the early 1980s: the identification of an accretionary prism offshore beneath the shelf and slope, the inboard part being elevated on land in the coastal hills south of Cape Kidnappers (Lewis 1980; Pettinga 1982). The juxtaposition of this Miocene accretionary prism with a Pleistocene volcanic arc (TVZ) has been the source of much speculation, and many explanations have been offered, some suggesting wholesale displacement by hundreds of km to the north. For reviews, see Kamp (1987) and King (2000).

Although rarely explicitly discussed, an underlying assumption has developed within the New Zealand geosciences community that the Hikurangi Trough through all of the Neogene has extended along its present extent (e.g. Barnes et al., 1998). The corollary is that subducted Pacific slab has lain beneath all of eastern North Island through most, if not all, of the Neogene, and that subduction accretion and kneading processes have dominated structural development of basins and intervening ridges along the margin since the early Miocene (e.g. Rait et al., 1991). The intersection of the backtracked positions of the Pacific slab edge with the Hikurangi Trough (Fig. 3) date the initiation of subduction at those points and suggest that the Hikurangi Trough lengthened to the south through the Neogene. The ages at the intersection points may be minimum ages if there has been substantial south-westward movement of upper (Australia) plate involving Wellington and Wairarapa as a consequence of drag imposed by the emplacement of the underlying slab (e.g. Kamp 1987). However, from the new plate rotation parameters the Pacific slab was emplaced beneath the upper plate in the fashion indicated in Figs 2 and 3. This implies that the accretionary prism south of Cape Kidnappers can be no older than late Miocene (c. 11 Ma). The remnants of early and middle Miocene sedimentary basins on land in southern Hawke's Bay and Wairarapa, cannot therefore have formed as accretionary basins, and are more properly attributed to having formed in a strike-slip regime as part of the Alpine Fault transpressive sector. Exploration concepts for these basins need to take into account structural overprinting from strike-slip to subduction regimes.

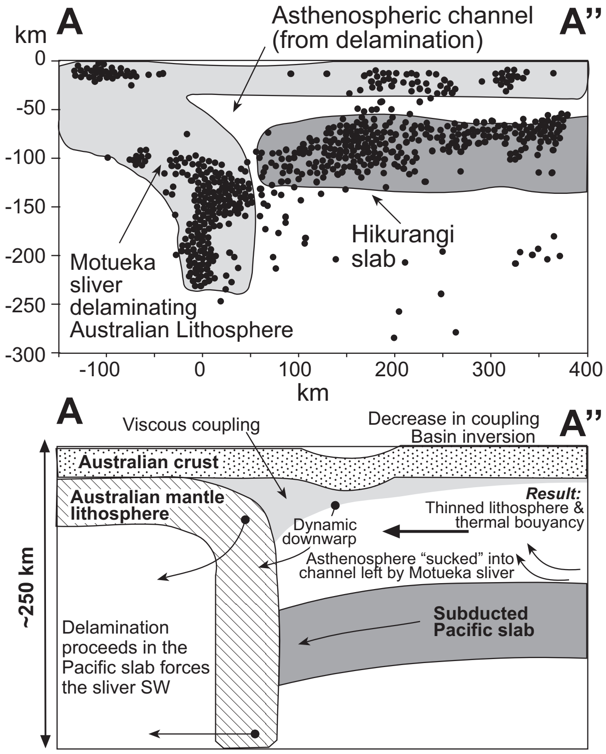

Figure. 8: *Seismicity projected onto cross section D-D' (Fig 4) or A-A' (Fig. 2) within 10 km of either side of a north-east-southwest profile parallel to the plate boundary zone, and beneath, a corresponding model/hypothesis of inferred lithosphere interactions and associated processes, that could explain the formation of sedimentary basins in western North Island (and subsequent inversion) that appear to have migrated southward with the leading edge of the subducted slab.*

Between East Cape and Cape Kidnappers, a subduction zone regime developed during the early and middle Miocene. It is possible that during this time the forearc region had a NW-SE orientation, orthogonal to the contemporary margin (Fig. 9). This is supported by several geological observations. (i) The Northland Allochthon and the East Cape Allochthon, which have similar content and timing of emplacement, were probably formerly continuous across Bay of Plenty (Kamp 1999), and were emplaced into the initial forearc basin parallel to the contemporary trench. (ii) A strong NW-SE trend is evident in isopachs for the middle Miocene Tununui Sandstone in northern Hawke's Bay (Davies et al., 2000). (iii) Thermochronological data integrated with regional stratigraphy indicates south-westward migration of basins and basement onlap along Raukumara Peninsula into northern Hawke's Bay during the early and middle Miocene, in sympathy with the direction of Pacific slab emplacement (Kamp 1999). The current NE-SW orientation of the forearc and structural grain in Hawke's Bay and the East Coast generally, probably dates from the Late Miocene (Kamp and Xu, 2002), and will have overprinted the earlier (early Neogene) structures. This needs to be built into exploration concepts.

The Neogene basins in western North Island owe their origin to processes in the upper mantle, with broad wavelength flexural downwarping and subsequent upwarping. These depocentres (Wanganui and Otunui) probably do not contain viable hydrocarbon prospects, although many exploration wells were drilled within them during the 1940s-60s. The main significance for hydrocarbon exploration of developing new tectonic and geodynamic understanding of basin origin, and associated stratigraphic and depositional evolution, lies in the better understanding that emerges about the development of eastern Taranaki Basin. Research results coming out of the University of Waikato sedimentary geology group show that the Miocene marine succession on land in eastern Taranaki Peninsula and in the King Country region, is contiguous with that in eastern parts of northern Taranaki Basin: it records late-early and middle Miocene retrogradation of a continental margin towards the east, followed by late Miocene-early Pliocene north-westward progradation of a new shelf-slope-basin continental margin (Kamp et al., 2004). The rapid subsidence of Wanganui Basin to upper bathyal depths from c.4.7 Ma, captured

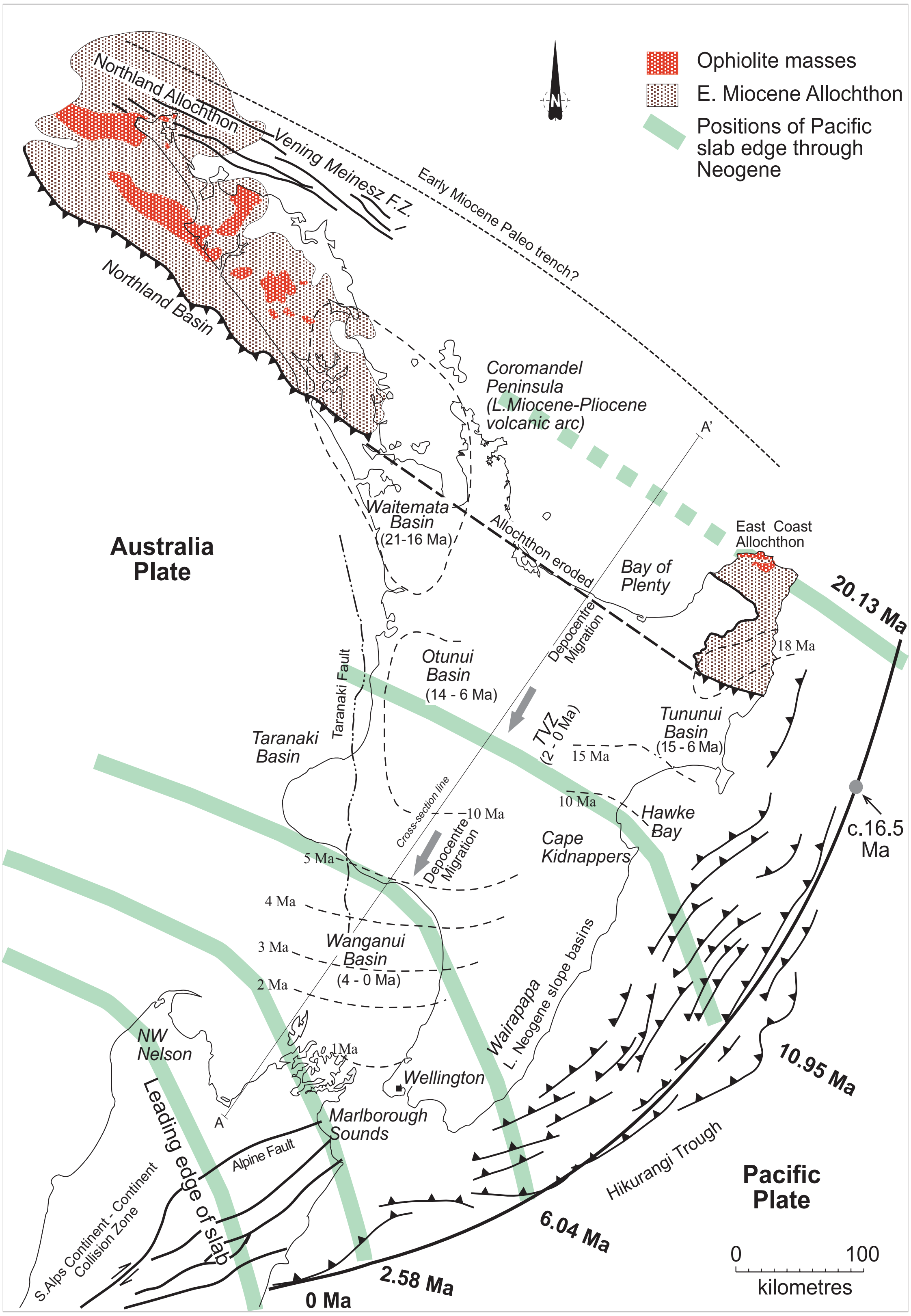

Figure. 9: *Map of North Island and northern South Island summarising elements of Australia plate geology and the progressive emplacement of the subducted Pacific slab beneath the region during the Neogene (from Fig. 3). Section line A-A' is the line of the time stratigraphic panel of Fig. 6. Subduction started at c.23 Ma along the north eastern continental margin, with the trench probably progressively forming towards East Cape. The Northland Allochthon and East Coast Allochthon where emplaced into a forearc basin rapidly formed inboard of the trench. Waitemata Basin formed during this early phase. Early to Middle Miocene basin migration to the southwest is evident south of East Cape, leading to the Tununui Basin. Approximate ages of basement onlap marking basin migration to the southwest are shown for Otunui and Wanganui Basins. The accretionary prism beneath the coastal hills of Hawke's Bay and Wairarapa and offshore beneath the shelf and slope is a late Miocene –Recent element.*

the siliciclastic sediment supply being sourced predominantly from the Alpine Fault – Southern Alps collision zone, shutting off the late Miocene-early Pliocene progradation, but then leading to a second phase (middle Pliocene-Pleistocene) of progradation in Wanganui Basin, the King Country region, and in Taranaki Basin that has built the modern continental margin in western North Island underlain in the offshore region by the Giant Foresets Formation (e.g. Hansen and Kamp, 2006). The successive formation and inversion of Otunui and Wanganui basins has had profound affects on the paleogeographic evolution of Taranaki Basin. During the Neogene there is an obvious southward displacement of crustal shortening along western North Island and in Taranaki Basin, and replacement by flexural downwarping, followed by crustal extension (e.g. King and Thrasher, 1996; Crowhurst et al., 2003; Kamp et al., 2004). This has been driven by a wider tectonic transition along the Australia-Pacific plate boundary from an Alpine Fault continental transpressive regime to a Hikurangi margin subduction regime, involving emplacement of Pacific slab into Australia plate upper mantle.

8. Concluding remarks

New information in this paper include backtrack calculations, using Cande and Stock Euler poles, of the emplacement through the Neogene of the subducted Pacific slab beneath Australia plate, and determination of the southward younging of the Hikurangi Trough. We have also presented new Neogene reconstructions of the Australia-Pacific plate boundary through New Zealand. These calculations and reconstructions have led us to think critically about the actual position and trend of the leading (southwest) edge of the subducted slab and its projection to the surface. We have suggested that it may lie north of the area of seismicity around Motueka, whereas prior interpretations have placed the slab edge further south in Westland. There are profound questions to be asked about how the Pacific slab has been accommodated within Australia plate lithosphere and underlying asthenosphere, and the geological manifestations at the surface. We have proposed a new model/hypothesis that invokes delamination of the Australia plate mantle lithosphere driven by the Pacific slab chisel, and which appeals to viscous drag of up welling asthenosphere on the base of the crust overlying the slab edge to form a basin that migrates with the advancing slab edge. The association of the Motueka cylinder of deep seismicity with a sliver of delaminated mantle lithosphere remains speculative at this stage. We have highlighted that in future, as shown here (Fig. 4) that cross-sections of mantle seismicity within the plate boundary zone need to be drawn in the plane of relative plate motion. Although this paper has focussed chiefly on new tectonic models, we have been motivated to develop them as a framework for better understanding the origins of sedimentary basins in North Island.

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