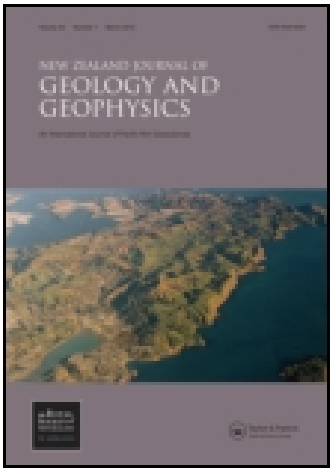

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Initial sedimentation and subsequent diagenesis in the Eastern Southland Lignite Basin, southern New Zealand

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The Eastern Southland Lignite Basin (ESLB) was initiated in the Late Oligocene at the same time that transpressional deformation began along the Alpine Fault. Initial sedimentation occurred near sea level, with interfingering of marine sediments and non-marine lithic conglomerates and associated lignite measures. Basal conglomerates are immature with rounded and angular clasts, and were locally derived from rising basement rocks on nearby basin margins. Conglomerates in younger lignite measures in the ESLB contain abundant quartz clasts derived from Central Otago schist, 100 km away, as well as some locally derived lithic material. Groundwater movement in the evolving basin caused pervasive clay alteration of lithic conglomerates and the underlying basement down to >10 m below the unconformity, as well as partial alteration of lithic clasts in sandstones. Alteration occurred under chemically reducing conditions and formed kaolinite, ferrous iron-bearing vermiculite-smectite and siderite. Post-depositional uplift in the ESLB has resulted in erosion of more than half of the sediments originally deposited. Erosion of the diagenetically altered rocks rich in clay left only minor residual quartz sand and gravel, with the bulk of the sediment being transported from the basin as clay in suspension or bed-load. In contrast, younger quartz-bearing conglomerates higher in the lignite measures sequence were recycled into the quartz-rich Pliocene conglomerates and younger gravels which now mantle the lignite measures over much of the basin.

Keywords: alteration; clay; lignite; Miocene; Oligocene; tectonics

Introduction

The Eastern Southland Lignite Basin (ESLB; Fig. 1A) includes an Oligocene–Miocene sedimentary sequence that contains more than 10 major lignite seams up to 20 m thick (Isaac & Linqvist 1990). The basin formed during localised basement subsidence with accumulation of more than 800 m of clastic debris (Isaac & Linqvist 1990; Suggate & Isaac 1990). The ESLB formed at the same time as the development of the Alpine Fault, a major transpressional structure that defines the Pacific–Australian plate boundary through southern New Zealand (Fig. 1A). Hence, the basin records the early stages in geological evolution of this tectonic zone, albeit distally from the main plate boundary. The lignite resources within the basin are large (>6 Bt). The nature of processes that occurred within that basin during its evolution is of economic interest for the ESLB and for helping to understand the processes of formation of large lignite basins elsewhere in the world.

Despite the economic significance of the ESLB, little is known about the earliest stages of formation of the basin because outcrop of the basal sediments and basement unconformity is poor within the basin area and those outcrops that are present are weathered. The geometry and coal quality of most of the lignite seams have been extensively investigated by drilling, and some of the shallower lignite seams have been exploited in small open-cut mines. However, none of the mines and, until recently, few cored drillholes have penetrated beneath the main lignite seams into the basal sediments and basement.

Renewed interest in utilisation of the lignites of the ESLB resulted in an extensive drilling programme in some of the most prospective parts of the basin in 2007 by Solid Energy New Zealand Ltd, and many of these holes were completed in basement. The Mataura and Croydon portions of the ESLB (Fig. 1B) were the principal targets during this drilling programme. Closely spaced drillholes provide a comprehensive new database for examination of the lignite measures, the basal sediments and the underlying basement in this area. This drill core database gives the first detailed three-dimensional view of the earliest stages of formation of the ESLB. Since these sediments contain little lignite, it is unlikely that any future mine will penetrate into this part of the basin. These cores therefore provide the only opportunity to examine evidence of geological processes that occurred near the floor of the ESLB during and after basin initiation. This paper provides descriptions of the geometry

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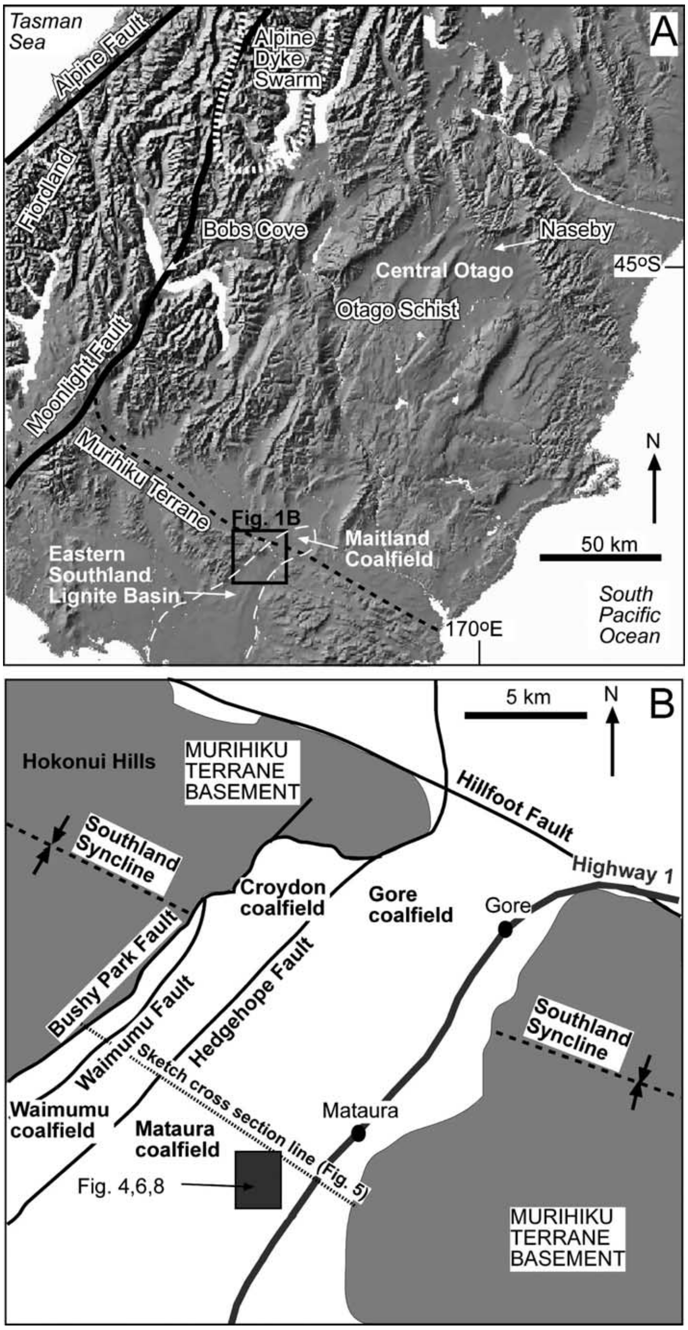

Figure 1 Location maps showing the topographic and geological context of the Eastern Southland Lignite Basin (ESLB). (**A**) Digital elevation model (DEM) (geographx.co.nz) of southern New Zealand, showing the principal basement rocks. The ESLB lies beneath the low relief area at bottom. (**B**) Structural map of the northern ESLB (after Isaac & Lindqvist 1990; Turnbull & Allibone 2003).

of the unconformity, descriptions of the basal sediments and observations on post-sedimentation diagenesis that has occurred above and below the unconformity; these observations are then linked to more general observations of the ESLB and surrounding geology.

General geology

Basement rocks

The basement for the ESLB is a sequence of Triassic–Jurassic arc-derived immature sandstones and siltstones, the Murihiku Terrane (Fig. 1A, B), which has been lithified and metamorphosed to zeolite facies (Campbell & Coombs 1966; Boles & Coombs 1977). These rocks have been folded into a regional syncline, the Southland Syncline (Fig. 1B). Bedding on the north limb of this syncline dips steeply south, and strike ridges of sandstone form prominent linear topographic features (Fig. 1A). Bedding is shallow-dipping elsewhere and almost horizontal in the hinge of the syncline beneath the Mataura coalfield, the principal area of interest in this study (Fig. 1B).

The Mesozoic Otago Schist belt to the north of the Murihiku Terrane (Fig. 1A) consists of sandstones and argillites that have been regionally metamorphosed to pumpellyite-actinolite or greenschist facies. Metasedimentary schists in the higher grade parts of the belt have pervasive foliation, and quartz-rich metamorphic segregations parallel to this foliation are 1–20 mm thick (Turnbull et al. 2001). The foliation is cut by scattered Mesozoic gold-bearing vein systems (Williams 1974). Crystalline rocks of the Fiordland crustal block to the west of the Murihiku Terrane (Fig. 1A) are mainly Mesozoic in age (Allibone et al. 2009).

Tectonic evolution

Extensional tectonism between middle Cretaceous and Oligocene time was driven by the breakup of Gondwana and subsequent initiation of a new plate configuration in the southwest Pacific Ocean (Carter & Norris 1976). This extension caused regional and local subsidence of the exhumed Mesozoic basement (Carter & Norris 1976). Subsidence facilitated marine transgression and associated deposition of a veneer of non-marine and marine sediments on the basement (Norris et al. 1978; Turnbull & Allibone 2003). Small extensional sedimentary basins developed especially near the Moonlight Fault (Fig. 1A); these were filled with predominantly marine sediments (Turnbull et al. 1975; Norris et al. 1978).

Regional subsidence ceased with the development of the Alpine Fault in the Late Oligocene, and transpressional tectonism caused uplift of mountains adjacent to the Alpine and Moonlight Faults at the north-western edge of the Otago Schist (Fig. 1A; Cooper et al. 1987; Craw 1995). This change to transpressional tectonics and uplift was accompanied by intrusion of an Oligocene–Early Miocene dyke swarm in the new mountains (Fig. 1A; Cooper et al. 1987). At the same time, the extensional marine sedimentary basins were compressively deformed, folded, faulted and locally filled with molasse deposits from the rising mountains (Norris et al. 1978). Transpressional deformation, uplift and erosion continued through to the present, with on-going localised basement uplift accompanied by localised subsidence and sedimentation in adjacent basins including the ESLB (Hatherton 1979; Isaac & Linqvist 1990; Youngson & Craw 1995). Uplift on the margins of basins has resulted in erosion and recycling of sediments from both the extensional and compressional stages of sedimentary deposition (Clough & Craw 1989; Youngson & Craw 1995; Youngson et al. 2006).

Cenozoic stratigraphy

The ESLB sedimentary sequence is dominated by the Gore Lignite Measures (Fig. 2) that were deposited during Late Oligocene–Miocene basin development. These sediments locally rest on, or are interfingered with, the Late Oligocene marine Chatton Formation (Fig. 2; Isaac & Lindqvist 1990). The Chatton Formation, and locally the Gore Lignite Measures, rest unconformably on Murihiku Terrane basement (Isaac & Lindqvist 1990). Pre-Chatton sediments have been eroded from beneath the ESLB and surrounding basement. Eocene non-marine sediments (Mako Coal Measures; Fig. 2) are locally preserved to the southwest of the ESLB, along with Early–Middle Oligocene marine sediments (Turnbull & Allibone 2003).

The upper parts of the Gore Lignite Measures contain some conglomeratic deposits and coarse sandstones interbedded with lignite seams (Isaac & Lindqvist 1990). These conglomerates contain abundant quartz clasts derived from the erosion of quartz-rich segregations in schist in Central Otago (Clough & Craw 1989; Youngson et al. 2006). The presence of detrital gold also supports a Central Otago provenance (Clough & Craw 1989; Youngson et al. 2006). Gore Lignite Measures are locally overlain by Late Miocene and Pliocene non-marine sediments that formed by erosion and recycling of Lignite Measures and earlier sediments, with additional contributions from rising basement (Clough

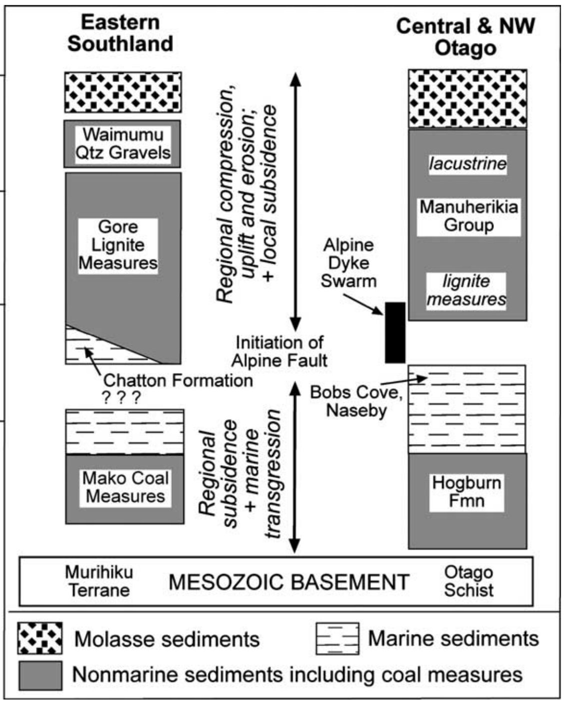

Figure 2 Summary stratigraphic columns for Cenozoic sediments of eastern Southland and Central Otago, with principal parallel tectonic events. See text for references.

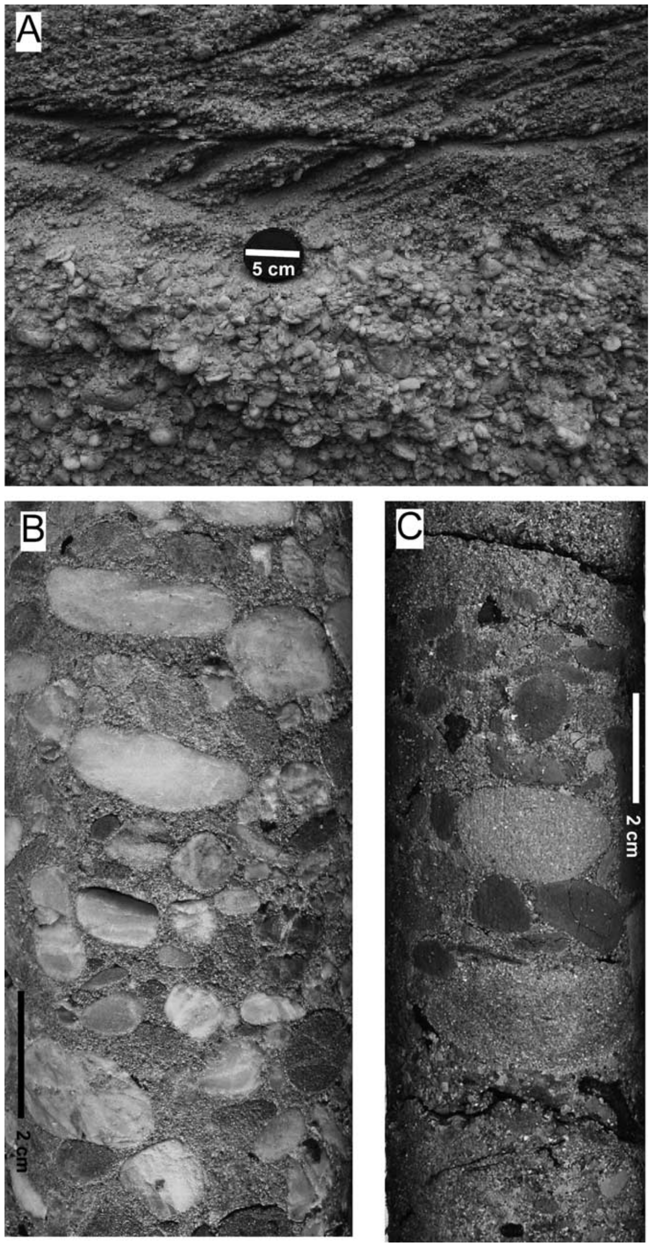

Figure 3 Photographs of conglomerates from some different stratigraphic levels in the ESLB, showing upwards increase in proportion of quartz clasts derived from Central Otago. (**A**) Outcrop of a lateral equivalent of the Waimumu Quartz Gravels (Pliocene; Falconer & Craw 2009). (**B**) Core through the upper part of the Gore Lignite Measures, Croydon coalfield. (**C**) Core through lithic conglomerate, basal Gore Lignite Measures, Mataura coalfield.

& Craw 1989). Quartz gravels with little immature lithic detritus (Fig. 3A) are widespread as a thin veneer on top of the ESLB, and these typically contain alluvial gold that has been concentrated by sedimentary and chemical recycling (Clough & Craw 1989; Falconer & Craw 2009). Pliocene and younger molasse sediments, with abundant immature detritus, overlie the quartz gravels adjacent to many of the rising mountain ranges (Fig. 2; Turnbull & Allibone 2003).

The Cenozoic stratigraphic sequence in the ESLB is broadly similar to that of the Central Otago area (Fig. 2), although little marine sediment is preserved in Central Otago. Shallow marine sandstones and limestones are preserved as slivers associated with the Moonlight Fault, notably at Bobs Cove, and shelly greensand is present at Naseby (Figs. 1A, 2). The Bobs Cove sediments were folded at the same time as the Alpine Dyke Swarm was emplaced (Turnbull et al. 1975; Cooper et al. 1987) and Manuherikia Group sedimentation was initiated immediately to the east. The Manuherikia Group contains abundant quartz gravels locally, especially near the base, and these are interlayered with and overlain by lignite-bearing sediments (Douglas 1986). The Manuherikia Group lignite measures are overlain by thick lacustrine sediments, and the lake that formed these deposits was filled by molasse from rising mountains in the Late Miocene and Pliocene (Youngson et al. 1998). The lower, lignite-bearing, portions of the Manuherikia Group are broadly correlative with the Gore Lignite Measures (Fig. 2; Douglas 1986; Youngson et al. 2006), but the overlying lacustrine sediments of the Manuherikia Group are not present in the ESLB.

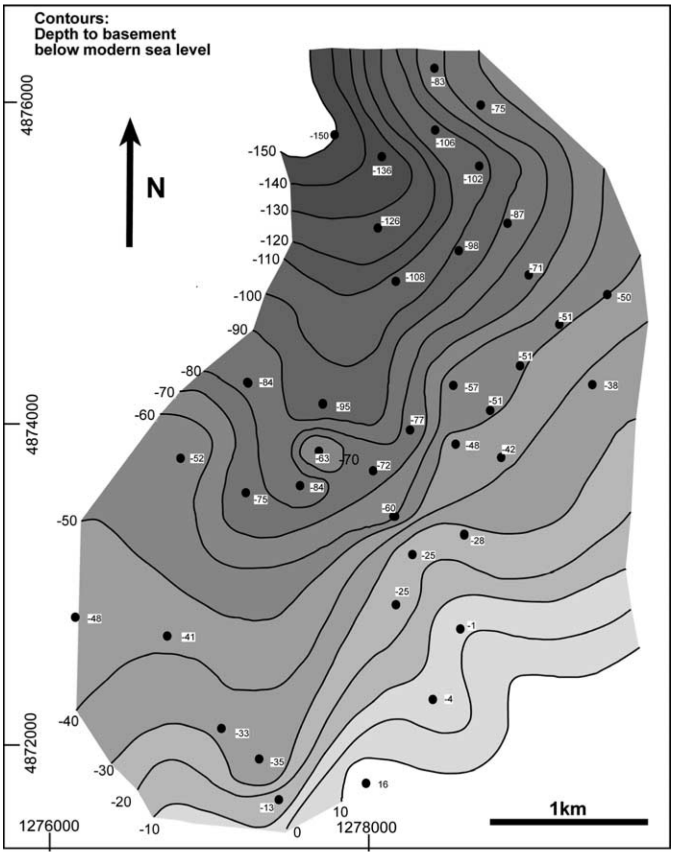

Figure 4 Contoured map of depth to basement, below modern sea level, in the Mataura coalfield (area indicated in Fig. 1B).

Methods

This study is based primarily on observations and samples from 39 drillholes distributed over a c. 10 km^2 area of the Mataura coalfield near the northern end of the ESLB (Figs. 1B, 4). All holes penetrated to the basement unconformity, and it is therefore possible to build a more accurate model of the basement unconformity (Fig. 4) than was possible in previous investigations (e.g. Isaac & Lindqvist 1990). Some holes continued more than 10 m beyond the unconformity, providing continuous unweathered core through the upper portions of the underlying Murihiku Terrane rocks.

Petrographic observations were made on hand specimens and in standard and polished thin sections of core to determine, analyse and interpret the variably altered basement, the distribution of marine sediments and the nature and distribution of conglomerates in the basal sedimentary sequence. The principal observed indicators of marine sedimentation were marine fossils, including foraminifera and macroscopic mollusc shells, burrows and the presence of glauconite.

Clay mineral alteration of basement and conglomerates in lignite measures was studied by petrography and X-ray diffraction (XRD). XRD spectra were obtained on air-dried powdered samples using a PANalytical X'Pert-Pro MPD PW3040/60 instrument equipped with a Rapid RTMS X'Celerator Detector system. Chemical analyses of clay minerals were obtained from one specimen of conglomerate using a JEOL JXA 8600 electron microprobe with an energy-dispersive analytical system. Beam diameter of 10–40 microns was used to limit specimen dehydration and to integrate analyses of masses of micron-scale grains.

Altered basement rocks were analysed by X-ray fluorescence (XRF) using a Philips PW2400 spectrometer. Samples were crushed and air-dried before formation into glass discs for analysis of major elements. Loss on ignition was determined after heating at 1100°C for 1 hour. Some samples absorbed moisture from the air during weighing, resulting in minor errors (< 1 wt%) that increase the analytical totals. The density of the basement was determined using a Geotek Ltd Multi-Sensor Core Logger (MSCL) equipped with a 137-Cs gamma-ray source and a detector consisting of a 5 cm diameter NaI(Tl) crystal and integral photomultiplier tube. Measurements were calibrated using an aluminium standard sample of known density and thickness.

Mataura Coalfield

Structure and basement rocks

The ESLB is structurally controlled by northeast-striking faults that cut across the general northwest strike of the Murihiku Terrane basement (Fig. 1A, B). The ESLB sediments are thickest (locally > 600 m) on the north-western margin of the basin, where the basin sediments have been folded and faulted into a complex structural zone (Fig. 5). This deformation has exposed basal marine sediments (Chatton Formation), especially along the Bushy Park Fault in the Croydon and Waimumu coalfields (Fig. 1B). In contrast, the Mataura coalfield is less deformed, and consists largely of planar or near-planar beds dipping gently westwards on a shallow-dipping unconformity (Figs. 4, 5). Bedding laps onto basement topography such as the Te Tipua High (Fig. 5) that existed during initial basin development (Isaac & Lindqvist 1990). The bedding was tilted to its present dip during subsequent deformation. The north-western margin of the Mataura coalfield is truncated by the Hedgehope Fault in a complex structural zone where bedding is commonly vertical and/or overturned (Fig. 5).

Basement rocks include shallow-dipping immature sandstones and siltstones, with minor lithic pebble layers (10 cm scale). Sandstones are well indurated and well sorted, with some diffuse planar and cross-bedding on a millimetre scale. Both fining-upwards and coarsening-upwards beds are present, often grading to siltstone beds. The sandstones consist predominantly of lithic fragments, mainly containing fine-grained plagioclase laths within an indeterminate groundmass. Potassium feldspar (~5%), clinopyroxene (~5%), scattered quartz grains and trace amounts of chlorite, biotite, hornblende, epidote, calcite and rutile are generally present. Clasts and matrix contain metamorphic zeolites (up to 15%), particularly laumontite. Siltstones are massive to weakly planar-bedded on a millimetre scale. They contain quartz, plagioclase, potassium feldspar and lithic fragments with trace hornblende, clinopyroxene, muscovite, chlorite and biotite. Swarms of veinlets (millimetre scale) of calcite, quartz and/or zeolites cut across the bedding.

Basal non-marine sediments

Lithic conglomerates occur in the deeper parts of the examined section of the Mataura coalfield at the northern end (Figs. 5, 6, 7A, B). The conglomerates vary from centimetre-scale layers to bodies several metres thick. They are typically restricted to one or two beds, interbedded with carbonaceous sands, within c. 1 m of the underlying basement unconformity. The conglomerates are commonly matrix-supported, with lithic pebbles distributed in coarse sand (Fig. 3C). Some very poorly sorted beds contain coarse clasts ≥ 6 cm diameter (core diameter). The coarser cobble conglomerates are predominantly clast-supported. Most clasts are subrounded, although some large angular clasts are present. Clasts are predominantly massive siltstone and fine-grained sandstone, with a lesser coarse-grained sandstone component. Rare red clay-rich pebbles occur, and some conglomerates contain carbonaceous fragments and small (centimetre scale) rounded coal pebbles. The conglomerate matrix is typically fine- to coarse-grained sand with a variable silt and clay fraction.

Carbonaceous sands occur as basal sediments in several cores from the southern part of the Mataura coalfield. These sands consist of thin beds of moderately well sorted but poorly indurated medium- to fine-grained sands, with a high silt fraction. The sands are variably carbonaceous, often bearing roots and/or streaks of organic detritus, with rare scattered pyrite grains (up to 2 mm) and polycrystalline nodules (up to 5 mm). The sands are typically centimetres to decimetres thick, interbedded in places with lithic conglomerates. The sands commonly fine upwards into overlying carbonaceous silt and mud beds, which are abundant in the basal sedimentary sequence (Fig. 7A, B). Some carbonaceous muds grade upwards or downwards over several centimetres into muddy lignites. The lowermost lignite horizons within basal parts of the Mataura Coalfield are typically thin (< 10–50 cm) and discontinuous with a high mud fraction (> 40%) and scattered pyrite grains.

Basal marine sediments

The marine sequence consists of several distinct, poorly indurated rock types within the Mataura coalfield cores

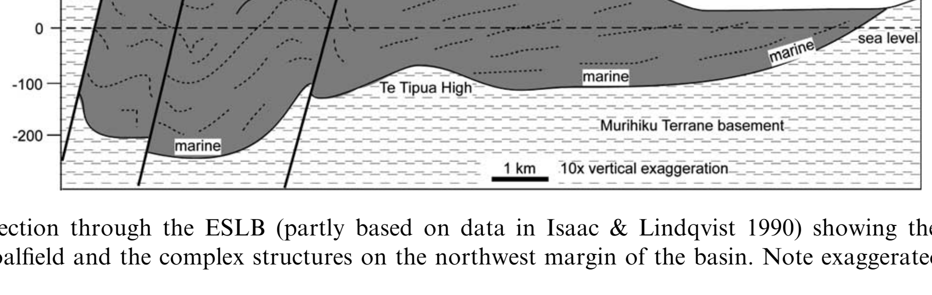

Figure 5 Sketch cross-section through the ESLB (partly based on data in Isaac & Lindqvist 1990) showing the structural relationship between the Mataura coalfield and the complex structures on the northwest margin of the basin. Note exaggerated vertical scale (× 10).

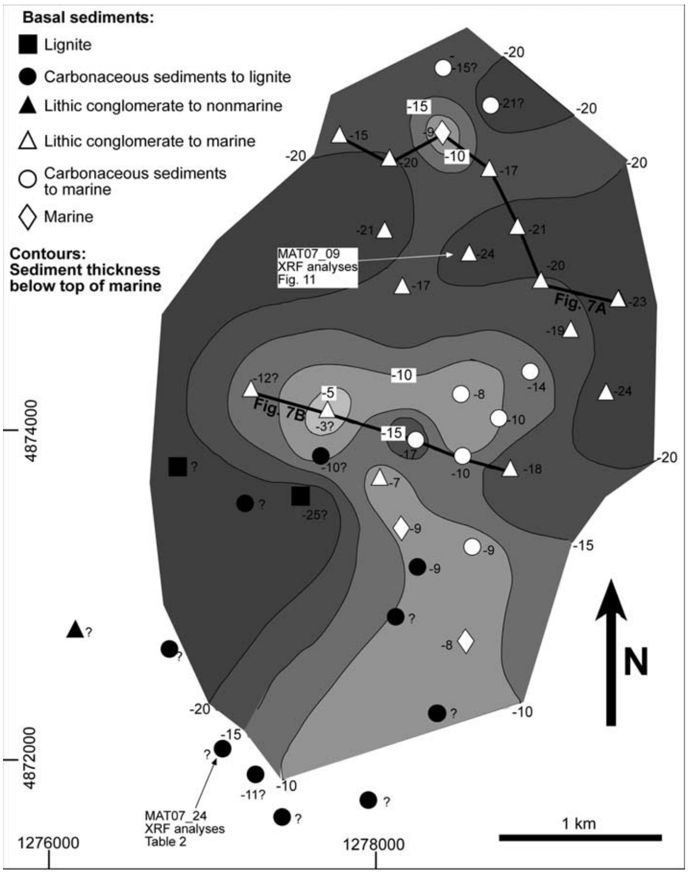

Figure 6 Contoured sediment thickness below the top of the marine sediments (inferred palaeo-sea-level) in the Mataura coalfield. The nature of the basal sediments in each drillhole is indicated with symbols.

(Fig. 7A, B). The lowermost marine sediments typically consist of carbonaceous sandy silt often bearing scattered shell fragments, and are commonly overlain by massive silt with scattered shell debris and concentrated shelly horizons. This silt layer is generally succeeded by coarser grained, upwards-fining sandy silt that generally contains scattered shells. Silts higher in the marine sequence are typically devoid of shells and have more organic matter. Contacts between the different rock types are often burrowed, forming distinctive marker beds that can be correlated between drillholes. The silts are composed of feldspar and quartz with subordinate matrix of clay and amorphous carbonaceous material, with scattered shell fragments and microfossils and variable amounts of glauconite and pyrite.

The above rock types typically occur at or within 14 m of the basement unconformity (Figs. 6, 7A, B). Where the marine sediments do not directly overlie basement they are immediately underlain by sands with carbonaceous streaks associated with lithic conglomerates, or carbonaceous clays associated with thin lignite horizons. The exact upper and lower contacts of the marine sequence are difficult to determine because of their gradational boundaries to non-marine facies (Figs. 6, 7A, B). However, most marine/non-marine boundaries could be determined within <1 m uncertainty. If the top of the marine sediments is assumed to be a palaeo-sea-level datum, then the thickness of the marine and non-marine sediments between this datum and the basement reflects the palaeotopography (Fig. 6). The same datum was used for construction of Fig. 7A and B. The marine sequence averages 8 m in thickness but varies from 3 to 13 metres thick (Figs. 7A, B, 8). The marine sequence is thinner in the west and thickens to the east within this part of the Mataura coalfield (Figs. 7, 8).

Clay alteration

Lithic conglomerates

All the lithic conglomerates are altered to clay to some degree, and most are almost completely clay-altered. Many clay-altered rocks have pale green colouration, particularly those with mafic detrital material. Clay alteration has not affected the macroscopic texture of the conglomerates, and sharp outlines are preserved in large clasts (Fig. 3C). However, the matrix of these conglomerates has been extensively altered, and clay mineral formation locally cross-cuts clast boundaries. Associated sands contain abundant lithic clasts; these have been clay-altered, but to a lesser extent than the lithic conglomerates. Mafic sand clasts, in particular, have been fully clay-altered, whereas feldspathic clasts still retain primary textures despite partial replacement by clay minerals.

Most of the clay is kaolinite (XRD identification), and this forms light-coloured microcrystalline (micron scale) masses that have replaced feldspathic detrital clasts (Fig. 9A). Scattered dusty inclusions in the kaolinite contain titanium (qualitative electron microprobe analysis), although the mineral species was not identified in this fine-grained material. Green clay minerals include chlorite and vermiculite-smectite (Fig. 10A, B; Table 1) that have replaced mafic clasts. Some clay minerals with elevated potassium and silica may be partially degraded muscovite, possibly with interlayered montmorillonite (Fig. 10B). Quartz clasts were unchanged by the alteration process (Fig. 9A). Scattered pyrite grains in sandstones appear to have formed in sandstone matrix as part of the alteration assemblage.

Basement rocks

Basement rocks are typically clay-altered more than 10 m below the unconformity, with the degree of alteration decreasing with depth. The alteration is texturally and mineralogically similar to that in the overlying lithic conglomerates. Alteration has been partly controlled by fractures in the basement rocks, and some spheroidal alteration textures and mottling are apparent in less altered zones. The inhomogeneities caused by differential alteration

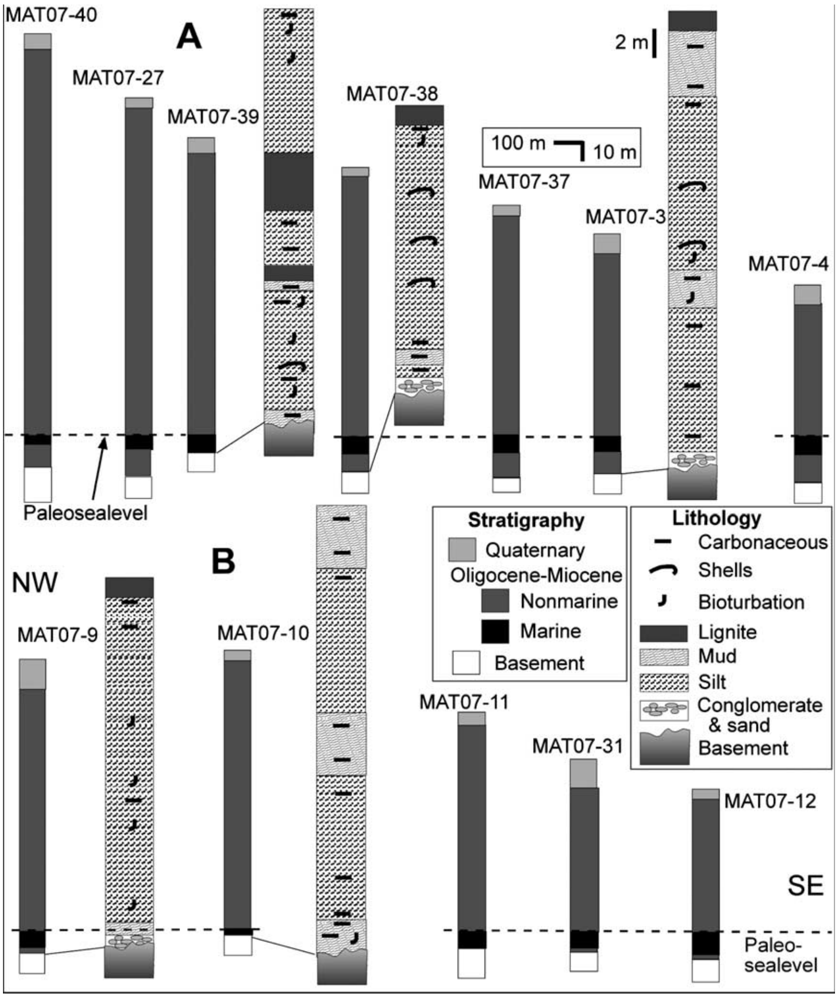

Figure 7 Summary stratigraphic logs of drillholes in cross-sections through the Mataura coalfield, along lines indicated in Fig. 6. (**A**) Northern section and (**B**) southern section. Note exaggerated vertical scale (in box in A). Summaries of representative lithological logs through basal sediments are depicted adjacent to selected stratigraphic logs. Bar beside MAT07-3 shows scale for all lithological logs.

decrease with increasing alteration, and textures are uniform in the more highly altered rocks. Altered rocks are mainly pale bluish-green, with a pinkish tinge locally. The unconformity between clay-altered basement and clay-rich basal non-marine sediments can be determined within 1–2 m accuracy. Irregular and branching carbonaceous streaks, generally vertical, occur in both basal non-marine sediments and in immediately underlying basement, and are probably coalified roots.

Kaolinite is the most abundant clay mineral in the alteration zone. Kaolinite replaces detrital feldspars, but clastic textures are preserved (Fig. 9B). In addition, mafic clasts and matrix have been replaced by fine-grained and/or coarse-grained birefringent vermiculite-smectite (Fig. 9B). The clay minerals are commonly accompanied by minor siderite in altered matrix. Quartz grains retain their clastic texture and are unaltered (Fig. 9B).

Increasing clay alteration towards the unconformity is reflected in the chemical analyses (Fig. 11). In particular, there is an increase in aluminium in the altered rocks and a parallel decrease in sodium, potassium and calcium (Fig. 11). This set of elements can be used to determine a chemical index of alteration (CIA), assuming that Al is relatively immobile compared to Na, K and Ca (Nesbitt & Young 1982). The CIA shows a distinct increase towards the unconformity (Fig. 11). Silica is also progressively depleted towards the unconformity. The loss on ignition (LOI) increases with increasing alteration and the density decreases with increasing alteration (Table 2), both parameters reflecting increasing hydration of the clay-rich rocks. A distinct deviation from these general trends occurs with a basement conglomerate sample c. 1.5 m below the unconformity. This conglomerate was apparently less permeable to alteration waters and is less altered than the surrounding rocks, resulting in higher FeO and K_2O and lower Al_2O_3 and CIA (Fig. 11).

Iron content of the clay-altered rocks is highly variable (Fig. 11), reflecting the irregular distribution of iron-rich

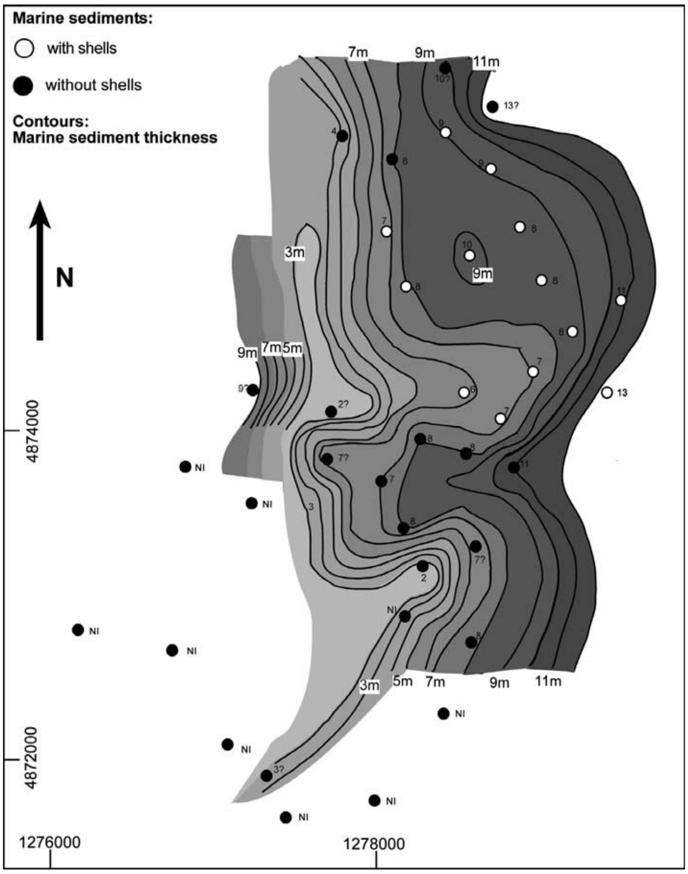

Figure 8 Contoured thickness of marine sediments in the Mataura coalfield. NI indicates that marine sediments were not identified.

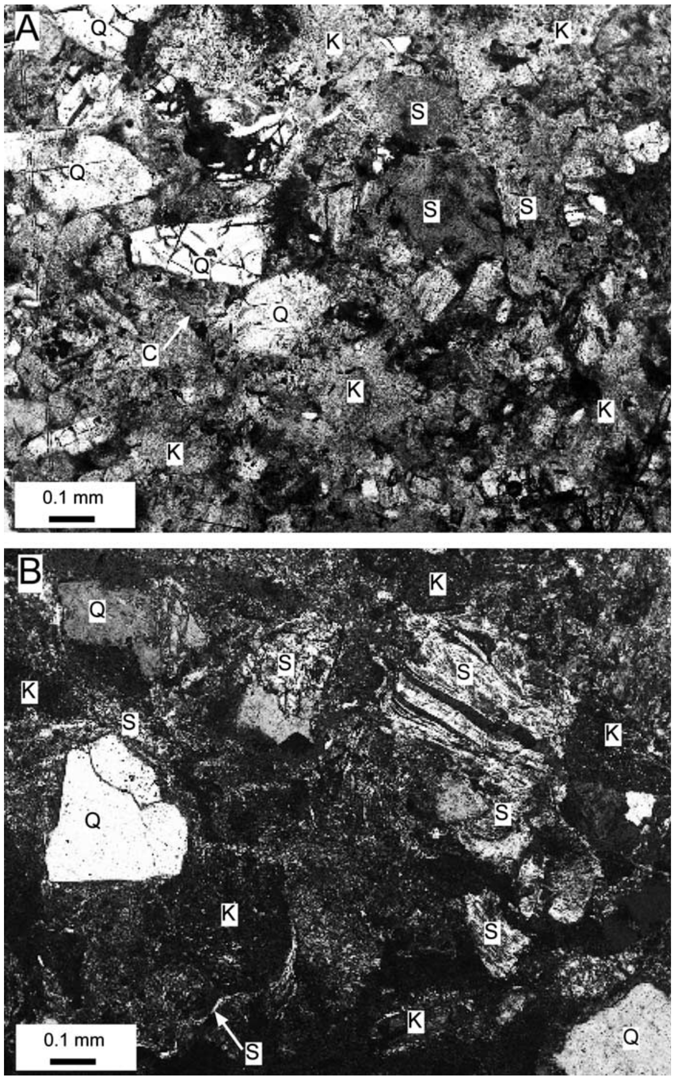

Figure 9 Photomicrographs of clay-altered rocks from beneath the Mataura coalfield. (**A**) Plane polarised light view of lithic conglomerate dominated by clasts altered to kaolinite (K) with some vermiculite-smectite (S) and chlorite (C). Quartz grains (Q) are unaltered. (**B**) Altered Murihiku Terrane basement sandstone viewed with crossed polars. Fine-grained kaolinite (K, dark and mottled) replaces most clasts, and vermiculite-smectite (S) is birefringent and light coloured. Quartz grains (Q) are unaltered.

vermiculite-smectite (Fig. 9B, Fig. 10). However, magnesium has been strongly leached from most altered rocks (Fig. 12A). Titanium content is largely unaffected by alteration in hole MAT07_24, but there has been approximately two-fold titanium enrichment in the most altered rocks of hole MAT07_09 (Fig. 12B), parallel to a relative increase in aluminium (Fig. 11). If it is assumed that titanium is immobile as for aluminium (Nesbitt & Young 1982) in low-temperature alteration solutions, as implied by the presence of dusty titanium minerals in the kaolinite (above), this apparent titanium enrichment implies substantial volume loss (c. 50%) during alteration. Volume loss presumably occurred via chemical leaching of more mobile elements from the rock mass in the most altered parts of the alteration zone.

Discussion

Timing of clay alteration

Both angular and rounded clasts in lithic conglomerates are intensely clay-altered, and these lithic clasts now readily disaggregate. These soft, friable clasts could not have survived sedimentary transport in their current altered form. In addition, clay mineral growth has locally cut across clast boundaries. These observations indicate that the clay alteration in these sediments must have occurred after deposition. Associated sandstones were apparently less permeable than the conglomerates, and have a lower degree of post-depositional clay alteration. The distinctive green Fe-K bearing vermiculite-smectite clay minerals in the ESLB lithic conglomerates (Figs. 9A, 10A, B) are similar to post-deposition alteration minerals described by Craw et al. (1995) in immature lithic conglomerates derived from the Otago Schist.

The strong similarities in clay mineralogy and textures in both basement and lithic conglomerate alteration zones

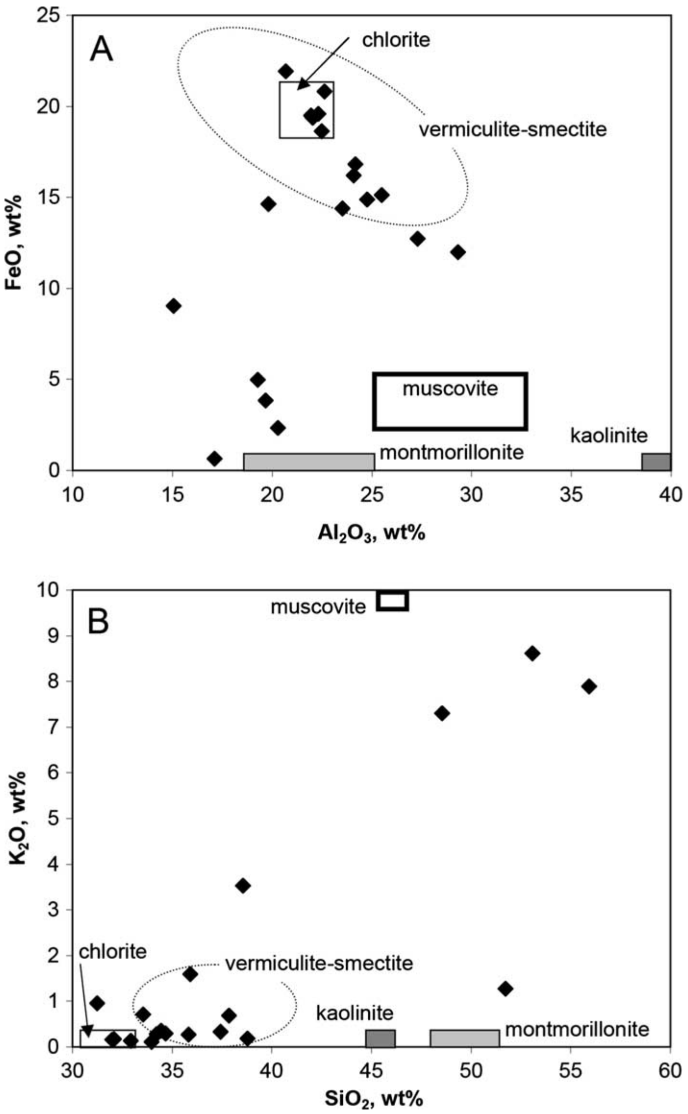

Figure 10 Scatter plots of electron microprobe analyses (black dots) of clay minerals in a lithic conglomerate from beneath the Mataura coalfield (Fig. 9A). Typical compositional fields for other phyllosilicates are indicated, including vermiculite-smectite from Craw (1984); dotted ellipse): (**A**) Al_2O_3 vs FeO and (**B**) SiO_2 vs K_2O.

suggest that alteration occurred at the same time in sediments and basement, i.e. after sediment deposition. In particular, the vermiculite-smectite clay mineral occurs in both basement and sediments. This mineral contains ferrous iron (Craw 1984), as does associated chlorite and siderite in these alteration assemblages. Hence, the alteration process occurred under chemically reducing conditions (Craw 1984, 1994). It is unlikely that such widespread reducing conditions prevailed in a subaerial weathering environment, so formation of these minerals in the basement alteration zones could not have occurred before sediment deposition. However, occasional near-vertical carbonaceous rootlets in the basement alteration zones indicate pre-depositional vegetation cover and, presumably, some soil development. Hence, the

Table 1 Representative electron microprobe analyses of clay minerals in a lithic conglomerate (Fig. 9A)

SiO_2	32.1	37.9	35.9	38.6	51.7	53.1
Al_2O_3	20.7	27.3	22.5	15.1	20.3	17.1
TiO_2	0.3	1.0	0.5	3.1	0.5	0.5
FeO	21.9	12.7	18.7	9.1	2.3	0.7
MnO	0.4	0.0	0.4	0.0	0.0	0.0
MgO	9.5	5.5	7.7	3.3	1.1	0.4
CaO	0.4	0.3	0.3	0.4	0.4	0.5
Na_2O	0.0	0.0	0.0	0.3	4.7	2.0
K_2O	0.2	0.7	1.6	3.5	1.3	8.6
TOTAL	85.57	85.26	87.55	73.21	82.33	82.85

basement alteration zones may be composite effects of both oxidised subaerial weathering and non-oxidised substratal alteration. Substratal alteration completely overprints pre-sedimentation alteration, as there are no mineralogical remnants of oxidative weathering. Substratal alteration of sediments and uppermost basement is widespread in southern New Zealand, and probably resulted from groundwater flow enhanced by active tectonic uplift on basin margins (Craw 1994; Chamberlain et al. 1999).

Syn-sedimentary pyrite formation is common in marginal marine coals in southern New Zealand, and the occurrence of pyrite in the basal non-marine sediments of the ESLB is therefore predictable (Isaac & Lindqvist 1990; Craw et al. 2008). Many of the lowest lignite seams in the ESLB have around 1 wt% S (Isaac & Lindqvist 1990), at least some of which occurs as pyrite grains visible in core. Likewise, glauconitic basal marine sediments also commonly contain syndepositional pyrite. Substratal groundwater flow and associated alteration can cause localised remobilisation and concentration of the marine-associated pyrite in coals and adjacent sediments (Craw et al. 2008). Hence, chemical mobility may be responsible for redistribution of pyrite into some basal sands in the Mataura coalfield cores examined in this study. This localised remobilisation of marine-related sedimentary pyrite is different from pyrite impregnation of non-marine sediments that occurs during chemical reduction of shallow groundwater that contains dissolved sulphate from marine aerosols (Youngson 1995). Pyrite deposited by the latter phenomenon can be irregularly present within shallow sediments in the ESLB (Clough & Craw 1989; Falconer et al. 2006; Craw et al. 2008).

Basin development

Formation of the ESLB and subsequent sedimentary deposition has been strongly controlled by the northeast-striking Cenozoic faults that define the complex structural zone on the north-western margin of the basin (Fig. 1B, Fig. 5). The abundant lithic conglomerates that occur at or near the basal unconformity indicate the presence of significant basement relief and active erosion at the time

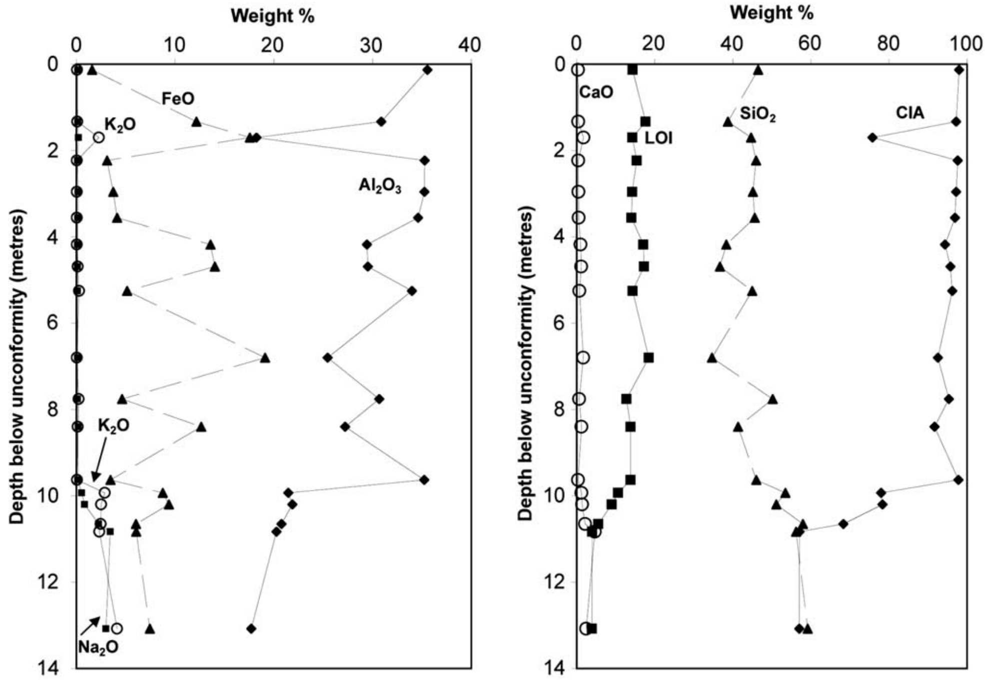

Figure 11 Major element variations (XRF analyses) with depth below the unconformity for samples collected through a basement alteration zone beneath the Mataura coalfield (hole MAT07_09; Fig. 6); LOI: loss on ignition; CIA: chemical index of alteration (after Nesbitt & Young 1982).

of basin initiation. The clasts in these lithic conglomerates are mainly immature sandstones and siltstones derived from immature sandstones and siltstones of the underlying Murihiku Terrane basement. The lithic conglomerate clasts were hard fresh rock prior to post-depositional alteration. Some clasts were rounded during transport although common angular clasts in the basal lithic conglomerates suggest local derivation from fresh basement. Soil formation undoubtedly occurred on this basement, although most of the clay alteration is post-depositional. All these observations suggest that there was active uplift and erosion occurring on the margin of the ESLB at the time of its initiation. This is in accord with the regional mountain uplift and associated sedimentary basin formation elsewhere in the southern South Island at the same time (Late Oligocene) at the initiation of the Alpine Fault and initial rise of the Southern Alps (Cooper et al. 1987; Craw 1995).

Sedimentation at initiation of the ESLB occurred at or near sea level, and the lithic conglomerates and accompanying carbonaceous non-marine sediments interfinger with marine sediments at the basement unconformity in the Mataura coalfield and elsewhere (Fig. 5). Ongoing tectonic deformation has resulted in progressive subsidence of the basin floor, but sedimentation kept pace with this subsidence to maintain predominantly non-marine conditions in the ESLB since the Early Miocene. Basin subsidence and non-marine sedimentation have been most rapid on the north-western side of the basin where $>$800m of sediment have accumulated, of which more than 600 m are locally preserved (Fig. 5; Isaac & Linqvist 1990; Suggate & Isaac 1990). The Mataura coalfield accumulated only 400 m during this time (Isaac & Linqvist 1990), of which c. 200 m is preserved. The basin-forming compressional deformation has resulted in uplift of the margins of the basin and tilting of the basin floor in the vicinity of the Mataura coalfield (Figs. 4, 5). Relief was low (20 m scale) at the base of the Mataura coalfield as observed in this study, and consisted of a broad north-trending ridge (Fig. 6). Basement relief up to 160 m occurs elsewhere, however (Isaac & Lindqvist 1990). The marine sediments and interfingered non-marine sediments onlap from the east on to this shallow relief (Figs. 6, 8). Onlap occurred over non-marine sediments locally, especially in the northeast, and directly onto basement elsewhere (Figs. 6, 8). Minor marine incursions also occurred at shallower levels in the ESLB (Isaac & Lindqvist 1990).

The Manuherikia Group lignite measures of Central Otago (Fig. 2; Douglas 1986) were formed at a similar time to (possibly slightly before) the ESLB (Mildenhall & Pocknall 1989; Isaac & Lindqvist 1990; Pole & Douglas 1998). The Manuherikia Group basin constitutes a similar style of compressional tectonic basin near the developing Alpine Fault. Basal conglomerates in the Manuherikia Group were also locally derived from pre-existing conglomerates with rounded quartz clasts (such as Hogburn Formation; Fig. 2) and some angular quartz debris from schist

Table 2 XRF analyses of altered basement rocks from drillhole MAT07_24 (rock types sst: sandstone; sltst: siltstone). Depths are relative to the unconformity; density is in g cm^{-3}; all iron is presented as ferrous; LOI: loss on ignition; CIA: calculated chemical index of alteration (Nesbitt & Young 1982)

Sample	OU 80555	OU 80556	OU 80557	OU 80558	OU 80559	OU 80560	OU 80561	OU 80563	OU 80564	OU 80565	OU 80566	OU 80567
Rock	sst	sltst	sltst	sltst	sst	sltst	sltst	mixed	sltst	sltst	sst	sst
Depth (m)	0.28	0.58	1.70	2.24	2.48	3.83	5.76	7.52	7.80	7.86	8.34	9.80
Alteration	Strong	Strong	Strong	Moderate	Moderate	Moderate	Moderate	Weak	Weak	Weak	Weak	Weak
Density	2.13	2.10	2.16	2.29	2.19	2.35	2.46	2.61	2.62	2.65	2.59	2.55
SiO_2	48.8	53.6	56.2	60.6	57.4	61.2	61.6	61.1	62.1	62.0	58.8	55.0
TiO_2	0.64	1.15	0.90	0.93	1.08	0.87	0.82	0.75	0.76	0.66	0.90	0.93
Al_2O_3	34.8	30.9	28.0	20.4	22.3	18.9	17.9	16.2	15.5	17.1	16.8	18.0
FeO^t	1.38	1.51	1.22	3.77	4.97	5.02	5.51	6.36	5.32	4.57	6.79	6.31
MnO	0.01	0.01	0.01	0.04	0.06	0.06	0.07	0.12	0.11	0.07	0.12	0.10
MgO	0.28	0.61	0.56	1.53	1.20	1.84	2.05	1.98	2.24	1.71	2.25	2.38
CaO	0.27	0.35	0.39	0.76	0.68	1.04	1.53	3.03	2.60	3.84	4.02	6.31
Na_2O	0.08	0.08	0.22	2.13	2.99	2.75	2.74	3.56	3.26	3.46	3.68	2.15
K_2O	0.36	1.48	3.15	3.96	2.87	3.81	3.14	1.68	2.62	1.65	1.23	0.88
P_2O_5	0.50	0.09	0.23	0.13	0.13	0.11	0.18	0.23	0.87	0.16	0.18	0.20
LOI	13.3	11.3	9.4	5.8	6.2	5.8	5.1	5.7	5.1	5.8	6.2	8.4
Total	100.4	101.0	100.3	100.0	99.9	101.4	100.6	100.7	100.4	100.9	100.9	100.6
CIA	101	93	88	70	71	65	64	56	59	55	54	54

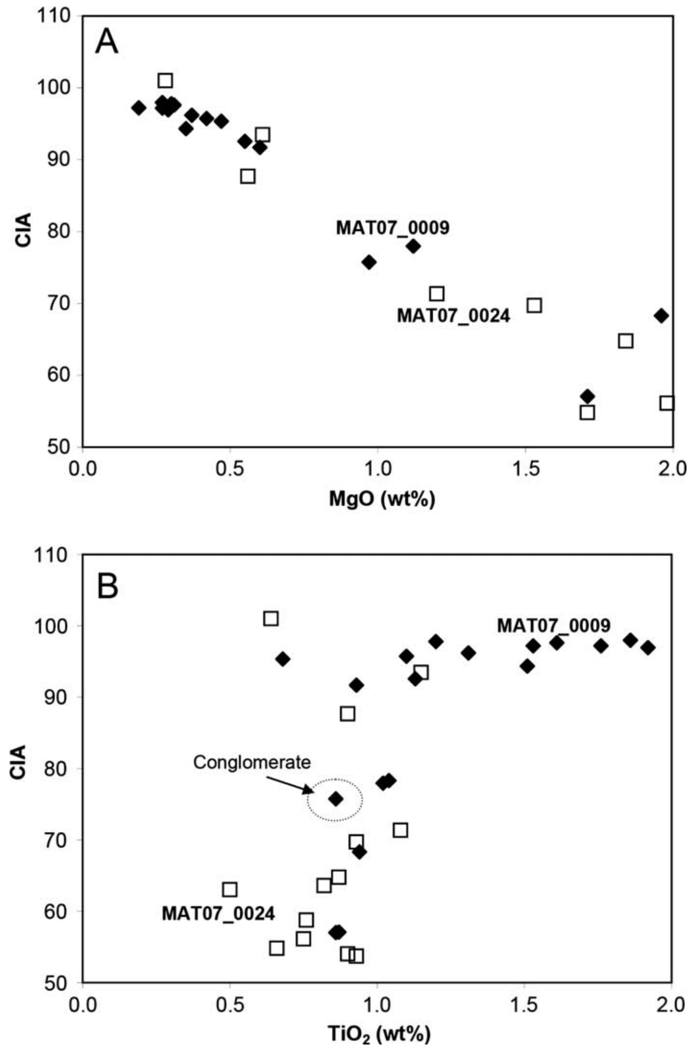

Figure 12 XRF analytical data for altered basement rocks below the unconformity under the Mataura coalfield, plotted in relation to the chemical index of alteration (CIA after Nesbitt & Young 1982). Dotted ellipse indicates a less-altered conglomerate layer (see text): (**A**) MgO vs CIA and (**B**) TiO2 vs CIA.

basement (Youngson & Craw 1995; Youngson et al. 2006). This tectonic origin and related erosion has removed any marine sediments from the basement surface, and Manuherikia lignites were formed in an environment that was not marginal marine like the ESLB (Douglas 1986; Youngson et al. 1998). Like the ESLB, the Manukerikia lignite basin of Central Otago was progressively deformed during the Miocene and Pliocene and has now been considerably disrupted by the rise of numerous basement ridges (Youngson & Craw 1995; Youngson et al. 2006). Late Oligocene–Recent deformation in Central Otago was at least partially controlled by pre-existing northeast- and northwest-striking faults (Turnbull et al. 1975, 1993). Similar structural reactivation may have controlled the ESLB, but all evidence of pre-Oligocene structure and stratigraphy has been eroded from the basin area.

Sedimentary provenance

Lithic conglomerates in the basal sediments of the Mataura coalfield are locally derived from the Murihiku Terrane basement. Sandstones associated with the lithic conglomerates in the Mataura coalfield also contain abundant immature lithic detritus from the Murihiku Terrane basement. This locally-derived immature detritus contrasts with mature quartz-rich conglomerates, derived from the Otago Schist (>100 km transport), which occur in the upper parts of the ESLB (Fig. 3A, B). Conglomerates in the upper parts of the Gore Lignite Measures in the Croydon coalfield (Fig. 1B) have abundant mature quartz clasts, combined with some locally derived immature detritus (Fig. 3B). There are no similar quartz-bearing conglomerates in the Gore Lignite Measures of the Mataura coalfield.

The conglomerate clast compositions suggest that sediments in the ESLB are derived almost entirely locally for much of the early history of the basin. Abundant lithic material in sands within the lower part of the sequence supports this contention. Hence, the ESLB and the lower Manuherikia Group were probably separate tectonic basins in the early parts of their history, although the base of the Manuherikia basin, as currently preserved, may be slightly younger than that of the ESLB (Fig. 2). Quartz-rich Late Oligocene–Early Miocene fluvial and estuarine sediments occur in the Maitland Coalfield to the east of the area of this study (Fig. 1A) (Pocknall 1982; Isaac & Lindqvist 1990). These quartz-rich sediments may represent the distal portions of the Manuherikia Group fluvial system that largely by-passed the ESLB. It was only in the latter stages of basin development that Otago Schist detritus (quartz and gold) began to dominate in the ESLB and mix with the locally derived material in the upper parts of the Gore Lignite Measures (Fig. 3B). This connection between the ESLB and Central Otago ended when the mountain ranges between them (Fig. 1A) began to rise in the late Miocene and Pliocene and immature molasse deposits derived from these ranges spread into the top of the ESLB (Fig. 2).

Uplift on the margins of the ESLB has been occurring since the basin's inception (above). This ongoing basement uplift has resulted in erosion of sediments from basement on both northwest and southeast sides of the basin (Fig. 5). Similar sedimentary recycling has been common throughout southern New Zealand (Youngson et al. 2006). In particular, recycling of auriferous quartz-bearing conglomerates results in redeposition of the quartz clasts and gold nearby within the basin (Clough & Craw 1989; Youngson & Craw 1995; Youngson et al. 2006). The net quartz and gold contents of recycled sediments at the top of the ESLB have been enhanced by removal by disaggregation of clay-altered immature clasts during recycling of conglomerates from the upper portions of the Gore Lignite Measures (Fig. 3B). For example, the extensively mined Waimumu Quartz Gravels (Figs. 2, 3A) consist almost entirely of quartz detritus because clay-altered material was removed during reworking (Clough & Craw 1989; Youngson et al. 2006).

Recycling of basal sediments from the ESLB and the underlying altered basement can yield little detrital quartz residue (Figs. 3C, 9A, B) and most of the eroded material must disintegrate to clays and be lost from the basin. The current volume of non-marine sediments preserved in the ESLB (Fig. 5) is less than half the original amount in this part of the basin, and the rest has been progressively uplifted and eroded. There may have been considerably more ESLB sediments resting on basement to the east and west of the present ESLB (Figs. 1A, B, 5), and any such sediments have also been eroded. However, the small proportions of non-labile debris in those sediments (Fig. 9A, B) means that there is likely to be negligible recycling record in younger sediments of the deeper portions of the ESLB sediments as they have been progressively uplifted and eroded by ongoing compressional tectonism.

Conclusions

The ESLB was at least partially fault-controlled, and formed during transpressional deformation related to the Alpine Fault. Basin formation and accumulation of lignite-bearing sediments occurred at the same time as the lignite-bearing Manuherikia Group of Central Otago, and both of these basins have been progressively uplifted and deformed by the same ongoing regional compressional tectonics. Initial sedimentation in the ESLB involved abundant immature lithic conglomerates and associated sandstones that were derived locally from rising Murihiku Terrane basement on basin margins. The basal conglomerates and associated lignite measures are interfingered with Late Oligocene to Early Miocene marine sediments, and sedimentation in the basin remained near sea level for much of its history. No evidence of earlier (pre-Late Oligocene) geological history is preserved in the basin.

The ESLB developed separately from the lignite basin in Central Otago, with little or no sedimentary connection initially. The Manuherikia Group lignite measures also contain basal conglomerates, but these are dominated by quartz derived from the underlying schist basement. Some quartz-rich sediment was transported from Central Otago in the latter stages of Miocene evolution of the ESLB. This sedimentary link between the two lignite basins continued to the Pliocene when mountain ranges rose between the basins, shedding new immature debris into the top of the ESLB.

Progressive deformation and uplift of the ESLB drove groundwater flow through the basin sediments and immediately underlying basement rocks. Chemical interaction between groundwater and labile rocks caused widespread clay alteration, which was most intense in lithic conglomerates and basement rocks within 10 m of the unconformity. The alteration occurred under chemically reducing conditions, and resulted in the formation of ferrous iron-bearing minerals and kaolinite. Some basement rocks have experienced two-fold enrichment of TiO_2 during alteration, implying 50% loss of other elements by chemical leaching. The substratal basement alteration may have been superimposed on rocks already weakly altered by subaerial weathering. However, most basement rocks being eroded during the initial stages of basin formation were fresh and hard, locally forming angular clasts in lithic conglomerates.

Progressive deformation and uplift of the ESLB has resulted in more than half of the sediments being eroded. The substratal alteration has ensured that these sediments consisted predominantly of clay minerals, with only minor quartz residue that has been resistant to alteration. Hence, erosion of the basal sediments in the ESLB (in the Mataura area at least) contributed negligible material to the recycled Pliocene and younger conglomeratic sediments that cap the basin. These younger capping sediments, which dominate the present surface topography of the ESLB, are made up of Central Otago quartz debris that has been recycled from conglomerates in the upper part of the ESLB.

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