SOUTH ISLAND AGGREGATE INVENTORY

Geological Influences on Materials Properties

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Intermediate Outcome 2
Aggregate Characterisation

SOUTH ISLAND AGGREGATE INVENTORY:

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Summary

Most aggregate produced for roading and concrete in the South Island is won from river and terrace gravels where the quality of the aggregate depends on the nature of the rock intersected by the river's course and the location in each watershed of the gravel or terrace deposit from which the material is extracted. The South Island has a much more complex geology and a more diverse range of rocks than North Island; consequently material in South Island gravels is more mixed and has a much wider range of physical properties than that produced from the greywacke-dominated North Island gravels. The type of greywacke contributing to the gravels in the Canterbury region is the strong quartzofeldspathic arkosic sandstone (Torlesse-Rakaia) which lacks the abundant clay-rich (and often swelling clay-rich) matrix of the volcaniclastic sandstones common in many parts of the North Island. Metamorphism, largely a function of depth of burial-related temperature increase, and strain associated with the major fault systems that transect the South Island, have converted these strong greywackes into weak mica-rich schists and gneisses. In most other parts of the South Island, different types of greywacke and other rock types are major constituents of gravels. The mixed nature of material in the South Island gravel deposits requires caution when making comparisons of test data and also raises questions about the applicability of some tests as an indication of the performance of aggregate produced from mixed-source gravels.

Basalt quarries in the West Otago and Banks Peninsula areas are generally good quality although they lack the strength of the Torlesse-Rakaia greywackes. The many other quarries in rock types other than greywackes, found particularly in the north of the South Island usually only produce aggregate for environmental protection, or in the case of limestones, for cement works.

1. PREAMBLE

The exposed greywacke basement of the South Island, the source of the majority of aggregates produced there, is more complex than that of the North Island. In some respects this is because the North Island is blanketed by young volcanic rocks, ash deposits, and Tertiary sediments which together cover large areas. However, in both islands the Murihiku, and the Torlesse (Rakaia / Kaweka and younger Pahau) terranes have wide geographic extent each having a degree of lithologic uniformity. But in the South Island, there are additional geographically discrete tracts of rocks each with a common geological nature and history: the Brook Street, and Dun Mountain-Maitai terranes, which each contain a wide variety of rock types in addition to greywacke-type sandstones. The Brook Street and Dun Mountain-Maitaia terrane rocks are grouped together with the Torlesse, Pahau, Murihiku, Waipapa and Caples terranes, into what geologists call the **Eastern Province**.

Greywacke sandstones of the Eastern Province have a variety of ages and compositions. Some were originally deposited 330 to 120 million years ago in submarine fans on the continental shelf. The inherent instability and consequent periodic collapse of these sediment piles swept sediment in large turbidity currents out onto the deep ocean floor; this is the mechanism of deposition of the sandstones of the Torlesse-Rakaia, Caples and Waipapa terranes. Other terranes contain sandstones that have been deposited in shallow water and near-shore marine environments.

However, unlike the North Island, the South Island also has exposed rocks which are both much older (by hundreds of millions of years!) than those of the Eastern Province and which also differ in terms of the types of rock they contain. These old rocks occur in the NW Nelson – Northern Westland and South Westland - Fiordland areas. On the basis of their age, the fossils they contain, and rock type similarities, they are considered by geologists to be parts of the Australian continental crust which were deposited 510 to 400 million years ago. These rocks are clustered together as the **Western Province**. Two terranes, Buller and Takaka terranes, are recognised in the Western Province. The Buller terrane contains a major greywacke resource in the Greenland Group. The Takaka terrane is dominated by carbonate sediments (limestones and dolomites) plus a variety of other sediments, many of which are shallow marine and volcanic-derived lithologies.[1]

In addition to having more complex terrane geology, the South Island has **plutonic igneous rocks and granulites** which are a significant component of the exposed geology. Coarse-grained granitic and granodioritic plutonics are concentrated in NW Nelson and Fiordland, while gabbroic rocks and granulites are also found in plutonic complexes in the southern part of the island.

The distribution of terranes and rock types in the South Island is largely the result of movement along the present-day **Australian – Pacific plate boundary**, which enters the South Island along the Wairau valley (Marlborough) and continues on a south-westerly trend paralleling the West Coast as the Alpine Fault before emerging to pass into the Southern Ocean along the Puysegur Trench (FIGURE 1). In northern New Zealand the active plate boundary lies offshore of the East Coast, localised on the Hikurangi Trough. The Western Province rocks and the westernmost of the Eastern Province rocks, of comparatively younger age, lie offshore of the west coast of the North Island.

Horizontal movement along the Alpine Fault has elongated the New Zealand landmass. In Southland the Murihiku, Brook Street and Dun Mountain-Maitai terranes are well exposed and geographically extensive, but the same sequence, shifted northward by the Alpine fault, exposed in the hills immediately to the east of Nelson City are very compressed and quarries in very different rock types (basaltic rocks, calcareous sediments and sandstones) and terranes, occur in thin fault-bounded slices often only a few tens of meters apart.

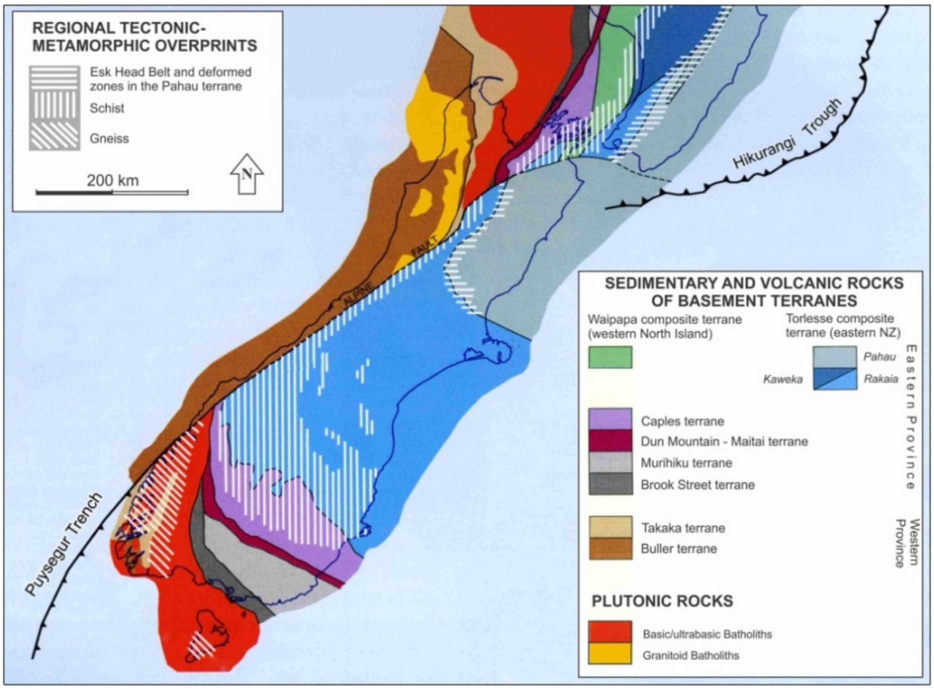


FIGURE 1 : Distribution of basement rock terranes exposed in the South Island and their connection/correlation with exposed greywacke terranes into the southern part of the North Island. The Alpine Fault is clearly indicated as a line which is the northern extension of the Puyegur trench

[1] R.A. Cooper (1989) Early Paleozoic terranes of New Zealand. *Journal of the Royal Society of New Zealand*, 19 (1) 73-112.

which exits into Cook Straight then curves eastward into Pacific Ocean. (Map is modified from Mortimer, 2004).[2]

While there are obvious correlations between the terranes in the North and South Islands and similarities in the rocks contained in them, the basement greywackes in the South Island have been subject to two processes which have affected them, and consequently the nature of aggregates produced from them, to a much greater degree than their counterparts in the North Island.

The first is the process of **metamorphism.** Vertical movement and crustal overthrusting along the Alpine Fault zone has thickened South Island greywacke sequences to such an extent that many have experienced higher temperature, pressure and strain environments than any of the basement rocks exposed in the North Island. With increasing temperature and in high strain regimes South Island greywackes greywackes have locally been converted into foliated and banded metamorphic schists and gneisses. Metamorphism and deformation convert what were originally strong high quality greywackes into weak rocks that have limited use in roading or in the concrete industry. The South Island has large expanses of such weak metamorphic (mainly schistose) rocks. In the North Island foliated or schistose rocks are very rare. Areas of schistose rocks are shown as vertical hachuring in FIGURE 1 and higher grade gneisses and granulites as diagonal hachuring in both cases superimposed on the parent rock, so as to indicate the nature of the parent rocks that have been altered and transformed (texturally and in terms of their mineral content) by superimposed metamorphism.

The second process is that of **glaciation**. Large parts of the South Island have been subject to several periods of severe glaciation, the first starting around 2.5 million years ago (i.e. at the beginning of the Quaternary). Under such severe climatic conditions the process of physical weathering is largely one of freeze-thaw expansion and the material is transported on or in the ice – thus the shapes of glacial gravels are different to those of gravels transported in turbulent water environments. The effects of glaciation are particularly notable in the Central Otago, Fiordland, and the Alpine regions of Canterbury. Deep depressions left behind when the glaciers melted are now the sites of lakes, and valleys filled with extensive fluvioglacial gravel deposits. These gravels have been reworked and transported to the coast by the many river systems that have their headwaters in the main divide.

2. GREYWACKES

In the South Island the majority of aggregates, whether produced from gravels or (much less commonly) by quarrying, have parent rocks called greywackes. For this reason the format of the following sections is to first describe the greywacke rocks concentrating on those of their properties relevant to their use as aggregate. These include changes that occur in the greywackes as the result of metamorphism and deformation.

2.1 Greywacke Types

Strictly speaking greywackes are a particular type of sandstone, although the term is very loosely used in New Zealand to cover all basement sedimentary rocks that were originally largely sandy in nature.

There are several classifications of sandstones in common international use. One of the most widely used is the Pettijohn[3] classification (FIGURE 2). This is also the most useful as far as aggregates are concerned because it does not carry with it any connotation of the genesis / origin of the sandstone (ie in deep or shallow water) instead one of the major criteria used is the percentage of matrix material.

[2] Nick Mortimer 'New Zealand's Geological Foundation' *Gondwana Research* 7 (2004) 261-272.

[3] F.J. Pettijohn (1975) *Sedimentary Rocks*; 3rd Edition. (New York)

According to the Pettijohn classification a greywacke sandstone has a matrix content in excess of a five volume percent. This distinguishes greywackes from matrix-poor sandstones which are called arkoses. However, 5% matrix, is very low and sandstones with such low levels of matrix are uncommon, so some sedimentary petrologists would put the boundary between arkoses and greywackes at 15% matrix.

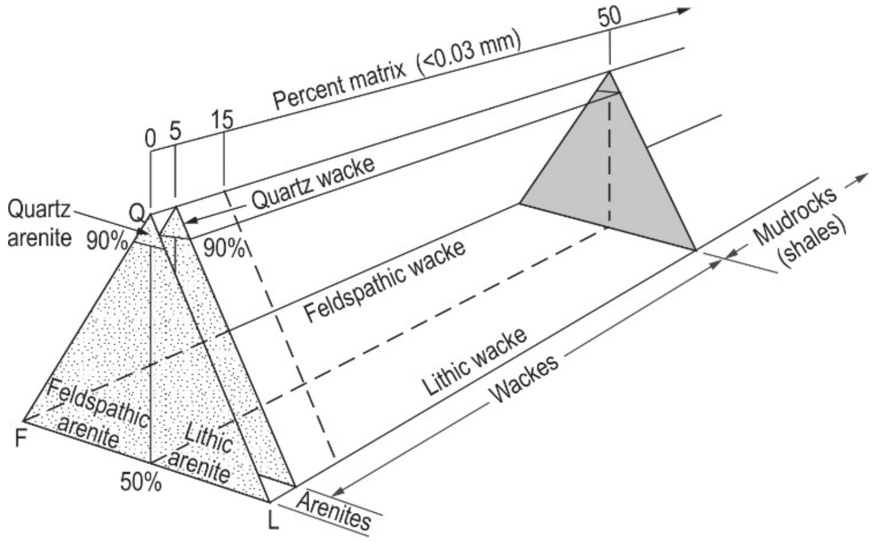
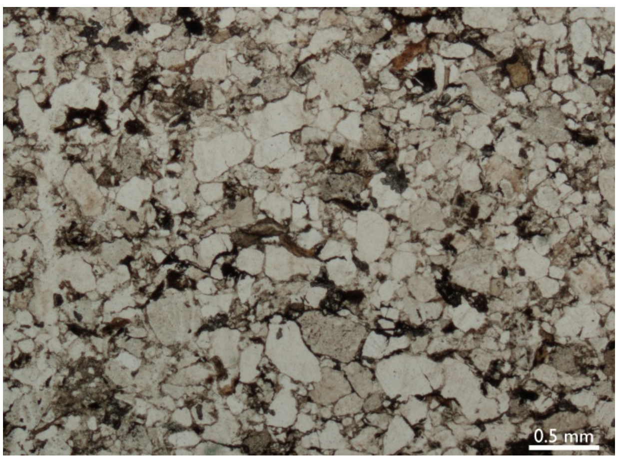


FIGURE 2 : Modified Pettijohn classification of sandstones. F = feldspar; Q = quartz and L = lithics (ie rock fragments).

The disadvantage of the Pettijohn classification is that it does not take into account the nature of the parent rock that has provided the sand and silt fragments (lithic grains) in the sandstone. This is an unfortunate omission because it is largely the detrital material that determines the rock's chemistry and consequently the minerals that will crystallise as the cement that lithifies (hardens) the sediment converting it into a sedimentary rock, and also recrystallises as new minerals during any imposed metamorphism. The mineral content of the rock will affect the rock's strength, its density (e.g. volcanic debris is more dense than quartz and feldspar), the rock's propensity to become foliated (and thus highly anisotropic), what clay and other minerals will form, and the nature of the weathered rock.



Microphoto Plate 1a and 1b : Plane polarised light. South Island arkosic sandstone (1a-left) and volcaniclastic lithic sandstone (1b-right); approximately the same scale. White mineral is quartz;

slightly grey mineral is feldspar; darker fragments – particularly notable in the volcaniclastic sandstone - are volcanic rock fragments; the slightly brownish mineral (just right of top centre in microphoto l b) is detrital pyroxene.

Based on their chemistry (and resultant minerals) four broad types of greywacke can be recognised in the South Island (FIGURE 3). Geological age is unimportant as a determinant of greywacke type but there is clearly a correlation between greywacke type and individual terranes.

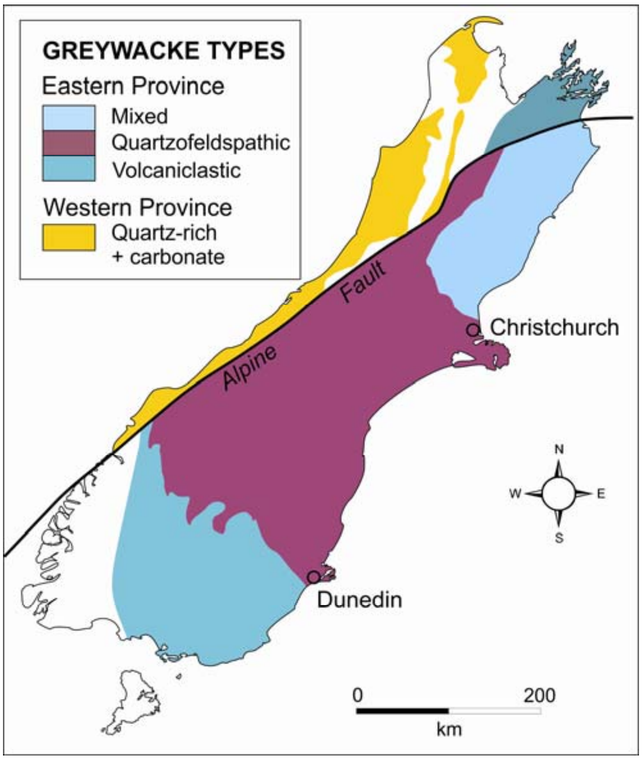


FIGURE 3 : Regional distribution of South Island greywacke types in terms of their mineral content and chemistry.

3. DIAGENESIS AND METAMORPHISM

The most important influence on the properties of the South Island's greywackes is the level of diagenesis – metamorphism that they have been subjected to.

Diagenesis is the process responsible for the 'hardening' of sediments, i.e. the conversion of a sediment composed of loose sand grains into a sandstone, by the geologically slow processes of compaction, recrystallization of detrital clay minerals, and the precipitation from interpore waters of new clay minerals and mineral cements. Diagenesis converts sediments first into weak rocks. As diagenesis proceeds the rocks become stronger materials although they may still maintain many of the features of the parent rock. In the sandstones, bedding and other sedimentary textures, even the outlines of individual sand grains, can still be seen although the matrix of the sediment becomes progressively harder and more crystalline and the rock stronger.

Diagenesis passes progressively into **metamorphism**. The agents that drive this progression are heat and pressure, both of which are largely a function of depth of burial. The Earth's **geothermal gradient** (depth versus temperature relationship) varies from place to place in Earth's crust and ranges from roughly 10°C per kilometre of depth in stable old continental environments to 30°C per kilometre of depth along active plate boundaries. Rocks are very good insulators; tectonic environments exist in which in which rocks are thrust down into the crust at faster rates than they are able to heat up and then rapidly uplifted so that minerals indicative of high pressure / low temperature environments are retained in the metamorphic rocks (blueschists and eclogites).

Sediments also contain pores which are filled with the water of the sediment's original depositional environment. This inter-pore water is driven off by progressive compaction of the sediments. During the passage from sediment to sedimentary rock and then, with increasing temperature into metamorphic rock, the sediments are progressively dehydrated. Large volumes of water are incorporated into diagenetic clay minerals of various types and zeolites. Clay minerals contain very significant amounts of water bonded into the mineral's molecular structure as well as water adsorbed on to the surface of the clay plates. Approximately 20% of a smectite's weight consists of bonded plus adsorbed water. When smectite reacts to form chlorite in weakly metamorphosed sediments approximately half of the smectite's water is lost in the reaction.

Minerals, other than clays, also react as temperature increases and break down to release their volatile components. Hydrocarbons are liberated as organic material in the sediment matures and CO_2 is liberated by the breakdown of carbonates, but these are usually minor in comparison with the huge volumes of water liberated by stepwise breakdown of clay minerals and dewatering the sediments in the first few hundreds of degrees of heating (up until around 250°C). Minerals such as clays (and zeolites), which are also strongly hydrous, are generally no longer stable above 250°C.

While the rock still has a significant permeability the volatiles liberated by dehydration and other reactions pass into the hydrosphere. However, with compaction and the onset of recrystallisation of the matrix of the sediment there is a consequent loss of permeability. Water cannot escape until the fluid pressure exceeds the confining pressure and hydraulic fracturing occurs.

Most mineral breakdown reactions occurring with increasing temperature in normal sandstone convert rock-forming minerals to new product-minerals that are less rich in silica. While some of this free silica precipitates in the matrix of the sediment as quartz cement, much silica is also transported out of the rock in the hydrous fluids as the rock dehydrates to be either redeposited in open fractures and joints as vein quartz or is removed entirely from the rock system to be lost into the hydrosphere.

Throughout metamorphism, with increasing pressure (depth of burial) minerals recrystallise to form new minerals. Less hydrous minerals form from hydrous ones, and these new products in their turn break down and ultimately crystallise as anhydrous minerals. At very high temperatures rocks melt. A rock's melting temperature is determined by its chemistry; alkali-rich rocks may start melting at temperatures around 600°C while refractory iron, magnesium and aluminium-rich rocks will not melt until temperatures exceed 1000°C.

Traditionally geologists allocate the different stages of metamorphism to what they call diagenetic and metamorphic facies. It should be noted that the transition from diagenesis to metamorphism is a continuum and may happen faster (i.e. at lower temperatures) in some rocks in comparison with others of different mineralogical / chemical composition. Thus facies fields are usually shown, as in the FIGURE 4 to be surrounded by transitional zones.

Minerals formed in the zone of diagenesis are all hydrous. Different types of clays and zeolites characterise the zeolite facies. The maximum temperature range for the diagenetic zeolite facies is around 200-250°C. The prehnite-pumpellyite facies is characterised by lack of zeolites and the general absence of swelling clay minerals; it has an upper stability range of around 300°C. In the North and South Islands the Murihiku provides an example of zeolite facies rocks while the Waipapa and Torlesse -Rakaia greywackes are prehnite-pumpellyite facies.

The amount of fluids liberated by dehydration reactions through diagenesis and into low temperature greenschist facies (the lowest temperature metamorphic facies) is very substantial. By far the most water is released between 250 - 300°C (depending on pressure) which is in the prehnite-pumpellyite facies field. By the time the zone of granulite facies is reached, metamorphic rocks are essentially anhydrous. As the rocks have become stronger through the diagenesis, zone fluids released by breakdown of minerals find it more and more difficult to escape. When fluid pressure built up exceeds the rock's confining pressure, hydraulic fracturing opens up the rock and liberates the fluids. But the sudden drop in fluid pressure following fracture causes elements leached out of the parent rocks and carried in the fluids (most commonly silica and alkalies) to precipitate out as quartz and sometimes sodic feldspar or the minerals calcite and/or prehnite which seal the joints. Mineral-filled veins are common in rocks of the prehnite-pumpellyite facies.

In the two diagenetic facies, zeolite and prehnite-pumpellyite facies, greywackes which consist of sand grains and a matrix have not been chemically homogenised and many components of the parent rocks (commonly the detrital sand grains) do not change. Nevertheless rock chemistry is important as it controls which minerals will crystallise. In particular smectites (swelling clay minerals) appear to require significant levels of magnesium;[4] which is why smectites occur in volcaniclastic greywackes. Under the same temperature – pressure conditions, the quartzofeldspathic sediments such as the Torlesse greywackes, are dominated by the non-expanding clay mineral, illite. With increasing metamorphism, the smectite clays convert to chlorites in rocks high in iron and magnesium (ie volcaniclastic rocks) The presence of chlorite in significant amounts gives rocks a greenish colouration. In the quartzofeldspathic greywackes, the common iron-magnesium minerals are micas rather than chlorite and the schists are usually grey or black in colour.

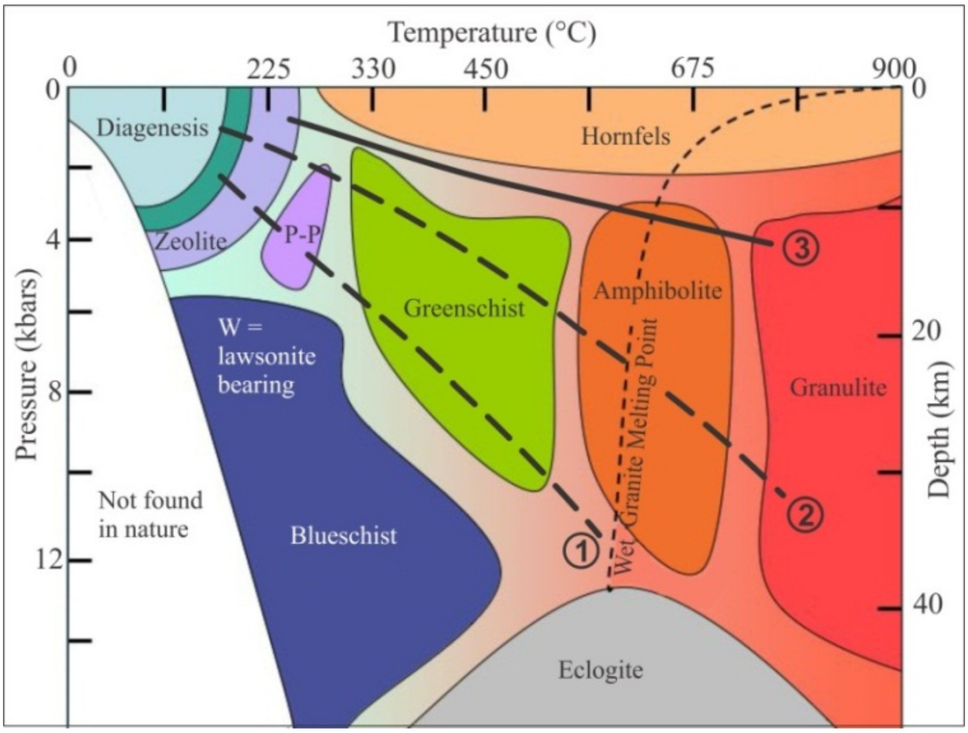


FIGURE 4 : Diagram showing the temperature/ pressure/ depth of burial stability fields of diagenetic and metamorphic Facies. Dashed lines (1) and (2) mark the geothermal gradient range for the greywackes of the Eastern terrane, although locally, associated with slices caught up in thrust zones high pressure lawsonite-bearing greywackes occur (area in blueschist P-T field indicated by w). The Western Terrane greywackes have high temperature/ low–pressure geothermal gradients with a

[4] Kloprogge, J.T; Komarneni, S. and Amonette, J.E. 'Synthesis of smectite clay minerals: A critical review'. *Clays and Clay Minerals* 47 (1999) 529-554.

generalised path shown by solid line (3). P-P = prehnite pumpellyite facies. Note : Quartz becomes ductile just inside the greenschist facies field.

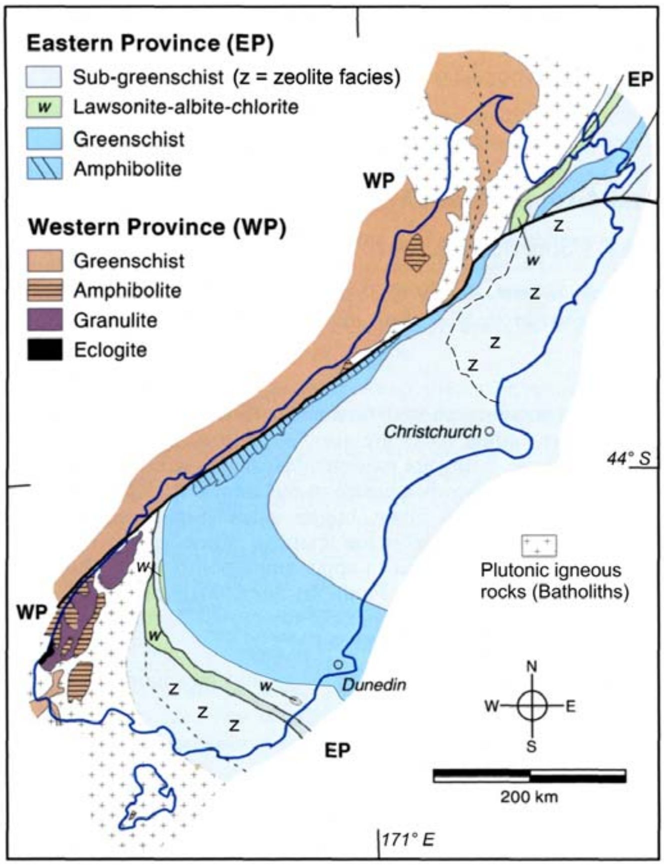


FIGURE 5 : Distribution of metamorphic facies in the South Island basement rocks. Note that in the Southland area the sub-greenschist rocks with z are all zeolite facies while in the North Canterbury – Marlborough area most of the rocks are prehnite-pumpellyite facies with localised occurrences (indicated by z) of zeolite facies rocks.

An important difference between the North and South Island basement rocks is that while the greywackes have all been affected to various degrees by diagenesis and metamorphism, the South Island greywackes have been exposed to higher temperatures and also to higher strain regimes. The strain effects are particularly important in that, at least in the range of temperatures (metamorphism) to which the greywackes have been exposed, rocks and minerals act to reduce the imposed strain in ways that change some of the rock's physical properties (e.g. its strength, and chip shape) which are important attributes of quality aggregates. The effects of imposed strain are the development within the rocks of a strong foliation, schistosity and ultimately gneissic textures. As a result, a parent rocks that would have produced quality high-strength aggregates becomes progressively weaker and has less suitable chip shape.

Release of water has another effect in that water reduces the viscosity of the rock and facilitates deformation.[5] In the zone of diagenesis, all common rocks react to stress as brittle materials. At higher temperatures, diagenetic conditions transition into the realm of metamorphism proper. The minerals in the rocks further dehydrate and the rocks react increasingly as more homogeneous units.

[5] Willner, A.; Massonne, H-J; Barr, S; and White, C. 'Very low- to low-grade metamorphic processes related to collisional assembly of Avalonia in SE Breton Island (Nova Scotia, Canada)'. *Journal of Petrology* (in press).

Textural features that are a function of metamorphism begin to replace those characteristic of the original parent rocks.

4 DEFORMATIONAL FEATURES

4.1 Textural changes: Rock and Mineral Reaction to Forces and Stress

Metamorphic rocks exhibit a variety of textures. These can range from textures similar to the original parent at very low grades of metamorphism, to textures that are purely produced during metamorphism and leave the rock with little resemblance to its original parent. These textural changes are important because they change many of the physical properties that are important attributes for rocks that are to be used as aggregate.

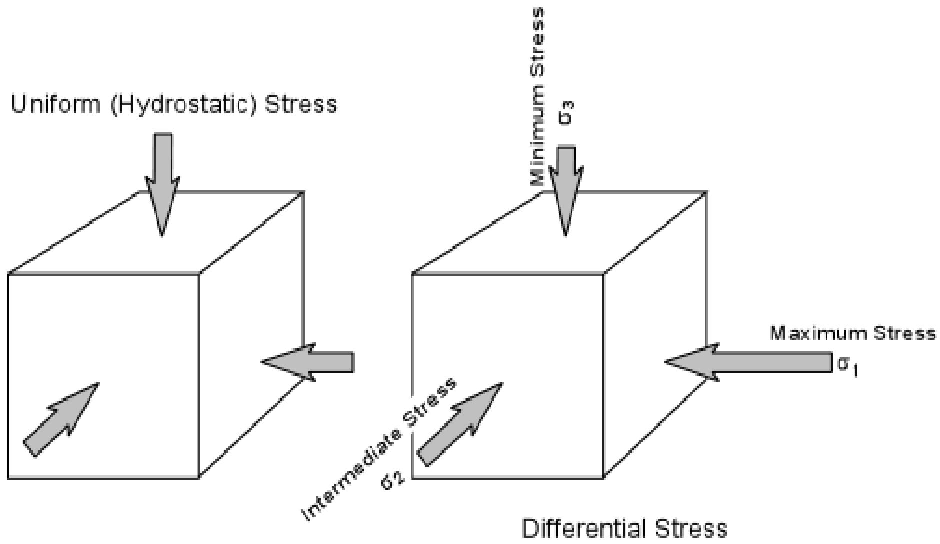
Most regionally metamorphosed rocks (at least those that eventually get exposed at Earth's surface) are metamorphosed during deformational events. Since deformation involves the application of differential stress, the textures that develop in metamorphic rocks reflect the deformational mode.

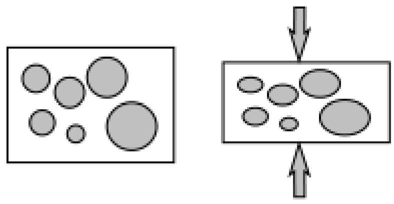
Rocks and minerals change their shape and volume when they are subjected to stress. A wide variety of physical processes exert stresses on rocks. For example, gravity constantly exerts downward stress on all rocks. Temperature changes cause thermal expansion and contraction that can cause rocks to fracture. On a large scale, horizontal plate movement exerts lateral (horizontal) and vertical stresses on rocks, and the accumulation of thick overlying layers of sediment can exert immense downward pressure. Rocks respond in two principal ways when subject to stress. They may deform in a **brittle** fashion, i.e. they fracture and fault. This is their behaviour in the zone of diagenesis (at low temperatures). At higher temperatures and pressures many rocks flow in response to stress – i.e. they deform in a **ductile** manner. Ductile behaviour is favoured by low strain rates.

Quartz, a strong / tough mineral at ambient temperatures and pressures, transitions from a brittle to ductile material at temperatures of roughly 335°C in the presence of water. Feldspar, another common mineral in greywacke, does not become ductile until temperatures close to 400°C.

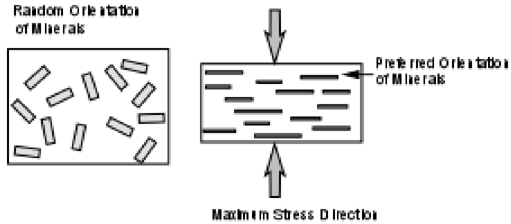
4.2 Stress and Preferred Orientation

Pressure increases with depth of burial, thus, both pressure and temperature will vary with depth in the Earth. Pressure is defined as a force acting equally from all directions. It is a type of ***stress***, called ***hydrostatic stress*** or ***uniform stress.*** If the stress is not equal from all directions, then the stress is called a ***differential stress.*** Normally geologists talk about stress as compressional stress. Thus, if a differential stress is acting on the rock, the direction along which the maximum principal stress acts is called σ_1, the minimum principal stress is called σ_3, and the intermediate principal stress direction is called σ_2. Extensional stress will act along the direction of minimum principal stress.

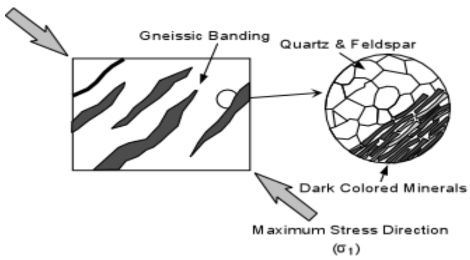




If differential stress is present during metamorphism, it has a significant effect on the texture of the rock. Rounded grains can become flattened in the direction of maximum compressional stress.



Minerals that crystallize or grow in the differential stress field develop a preferred orientation. Platy or sheet-like silicates (such as micas and chlorites) and minerals that have an elongated shape (eg amphiboles) will grow with their sheets or direction of elongation orientated perpendicular to the direction of maximum stress.

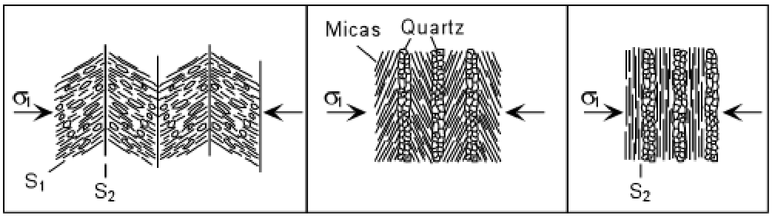


Because the dark coloured minerals tend to form elongated crystals, rather than sheet- like crystals, they still have a preferred orientation with their long directions perpendicular to the maximum differential stress. As temperature increases, the sheet silicates become unstable and are replaced by other minerals; like hornblende and pyroxene. These dark coloured minerals tend to become segregated into distinct bands through the rock and it gives the rock a ***gneissic banding***.

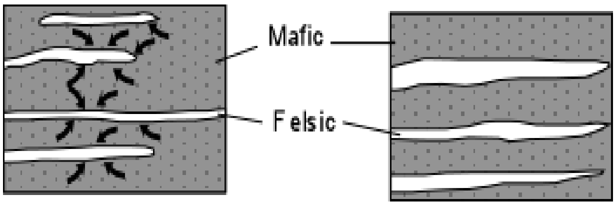
At high temperatures, such as in the granulite facies, micas, particularly muscovite, are no longer stable. The rocks become dominated by anhydrous minerals such as pyroxenes. Textures of metamorphic rocks become massive and equigranular to merge mineralogically and texturally with plutonic igneous rocks.

4.3 Solution and Re-precipitation.

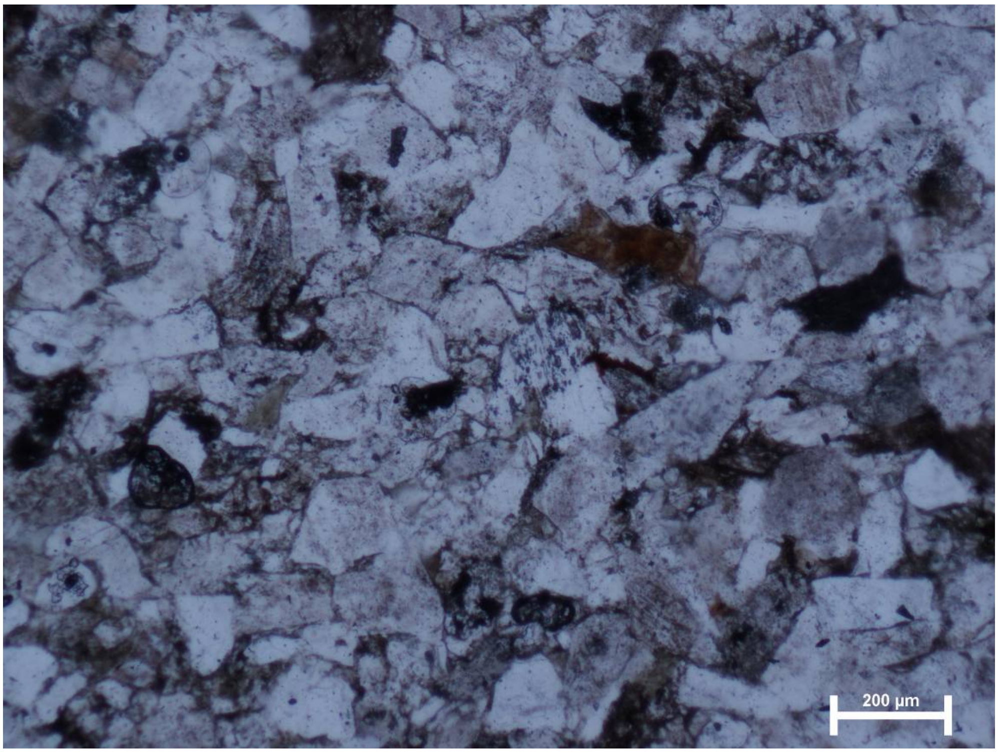
In fine grained metamorphic rocks, small scale folds often develop as the result of compressional stress. A new foliation begins to develop along the axial planes of these folds. Quartz and feldspar may dissolve as a result of pressure solution and be reprecipitated at the hinges of the folds where the pressure is lower. As the new foliation begins to align itself perpendicular to σ_1, the result is alternating bands of micas and/or chlorite and quartz or feldspar, layered parallel to the new foliation.



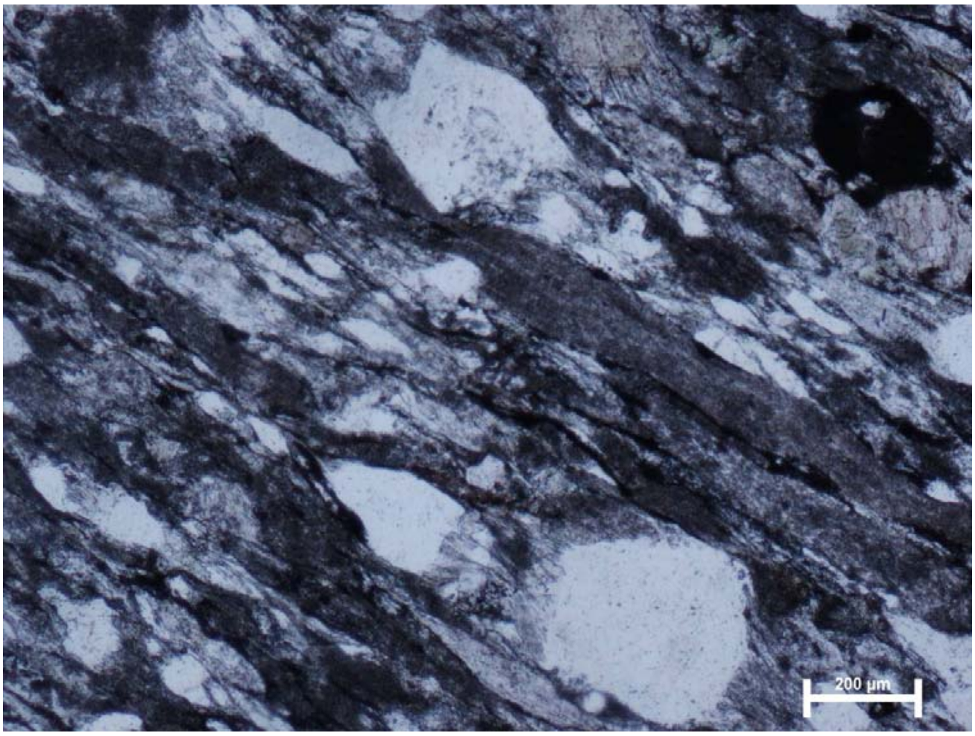
Thus felsic minerals could be dissolved from one part of the rock and preferentially nucleate and grow in another part of the rock to produce discontinuous layers of alternating mafic (dark) and felsic (light) compositions.

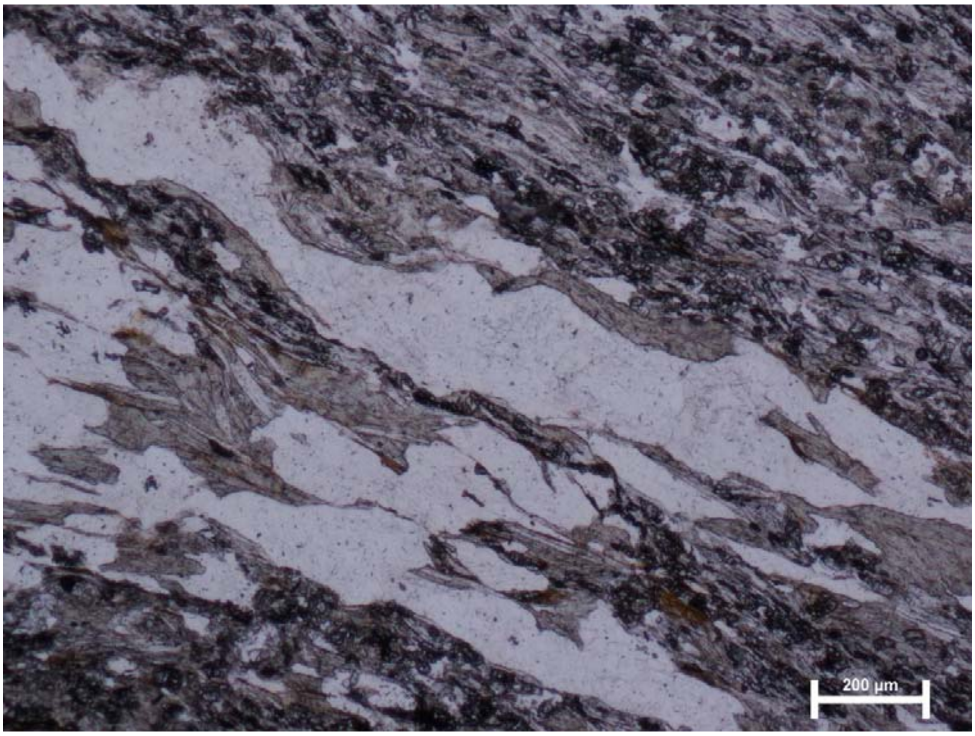


The following Microphoto plates 2 and 3 illustrate textural changes in Caples terrane sandstones which have been progressively metamorphosed and converted from sandstones to foliated schists.

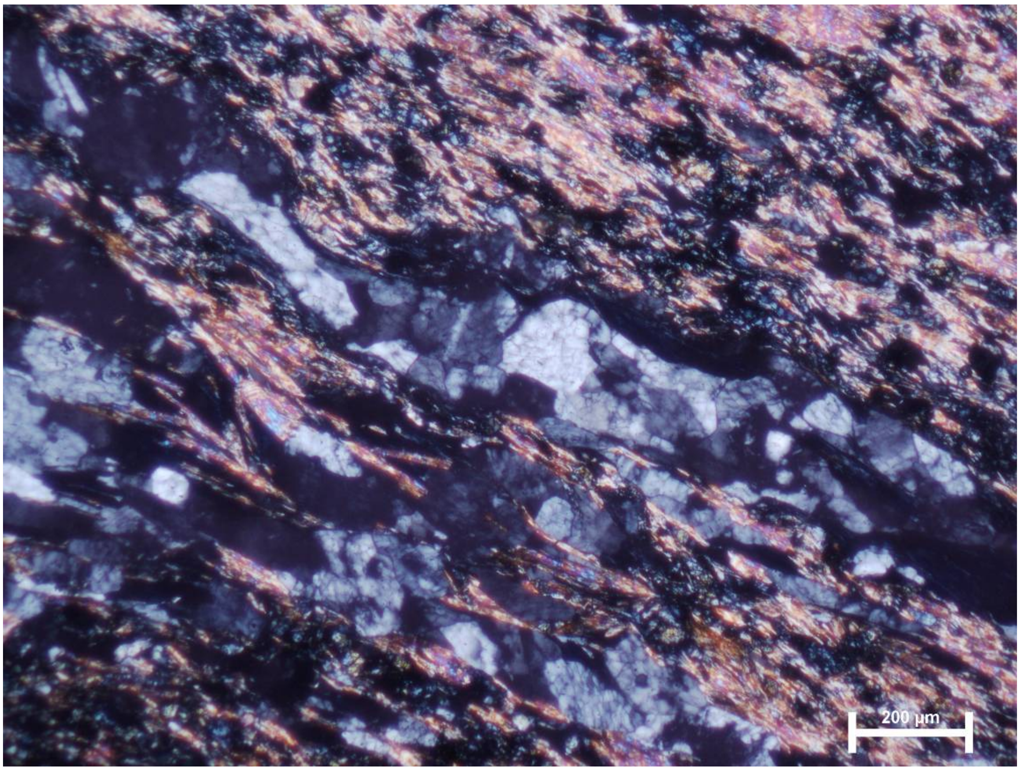


Microphoto Plate 2a and 2b : Thin section photos of diagenetically altered texturally unchanged volcaniclastic sandstone (2a above) and subschist (2b below). In 2b, note flattened mineral grains and new minerals growing from them, particularly in the lower right field where new minerals are growing parallel to the rock foliation in pressure shadows created by a large quartz grain.





Microphoto Plate 3a and 3b : Thinsection photos of strongly foliated schist. Same field of view but in plane polarized light (3a above) and between crossed polarisers (3b below). The white minerals in both views are quartz grains the coloured minerals (lower photo are micas.) Microphoto 3b : (below) shows completely recrystallised rock with segregation of quartz grains (white) from chlorite (brownish-green plates) , muscovite (white plates) and epidote (small granules).



4.4 Relevance of Textural and Metamorphic Changes to Aggregate Propertiess

The metamorphism of rocks in high stress environments, and consequent solution transfer effects, produce three changes that affect their physical properties and mineralogy, and hence the nature and quality of aggregate manufactured from the rocks:

(1) The strength of the rock is reduced as the result of recrystallization and segregation of mineral constituents into quartz-rich and either mica- or chlorite-rich layers. This weakening is most pronounced in quartzo-feldspathic rocks such as Torlesse-type greywackes which convert quickly into mica schists; the mica-rich bands in mica schists are very weak. Volcaniclastic rocks such as Caples-type greywackes contain more calcium, iron and magnesium and recrystallize into calcium-rich minerals such as epidote (which has a relatively equidimensional shape) and iron-magnesium-rich chlorite and amphiboles (platy and needle-like minerals respectively). While these epidote-chlorite-amphibole schists also have reduced strength compared with their parent rock, they are generally stronger than mica-schists.

(2) Crushing foliated source rocks produces platy-shaped chips since the foliation plane and mineral banding control the shapes of chips. Chips with a tendency to be platy are generally unsuitable for use in roading or concrete.

(3) Quartz-rich layers and veins, commonly formed in high stress environments in greenschist facies rocks, are significantly harder / tougher than other parts of the source rock, and consequently will be concentrated in gravels and result in a concentration in the aggregate of quartz-rich particles ("pepper and salt" aggregates).

Photo Plate 1 : The photo above shows mixed chips derived from schistose Caples terrane (greenish or yellowy-green chips) and Torlesse terrane (grey chips). Note the abundant white quartz chips which are dominantly derived from vein quartz, although some chips are clearly quartz-rich bands in the source rock schist. (Photo: Peter Mortimer, Downer)

5. BASEMENT TERRANES OF THE SOUTH ISLAND AS AGGREGATE RESOURCES.

While there is a connection / correlation between some of the basement terranes of the North and South Island there are significant differences in their outcrop extent and also, in some cases in terms of the nature of the same terrane in the two island. In large part this is due to differences in metamorphic grade between geographically distant parts of the same terrane.

Torlesse type greywackes are the most significant and distinctive aggregate source rocks in the South Island (and indeed New Zealand). These sandstones are composed of debris believed to have been eroded from the granitoid terranes of NE Australia.[6] The debris that is contained in the Torlesse sandstones consists of detrital quartz and alkaline feldspars and micas as well as fragments of quartz- and feldspar-rich rocks; technically they are either arkoses or quartofeldspathic greywackes depending on the percentage of the matrix.

The Torlesse sandstones are chemically very silica- and alkali-rich. When they recrystallise during early diagenesis and early metamorphism, quartz dominates as a matrix cement so these rocks are very strong. The Torlesse sandstones are also rich in mica-type minerals (illite in the rock matrix and biotite and muscovite as both detrital and metamorphic minerals). Weathering of these rocks tend to produce hydro-micas (vermiculite). Vermiculite is a 2:1 clay (that is it has two tetrahedral silica sheets and one octahedral sheet – which is the same basic structure as the micas and illite). Vermiculite clays are essentially weathered micas in which the potassium ions between the mica molecular sheets have been leached out and replaced by iron and magnesium ions. Vermiculite is a limited expansion clay with a medium shrink-swell capacity. It has a high cation exchange (100-150 meq/100 g).

[6] Adams, C.J.; Barley, M.E.; Fletcher, I.R. and Pickard, A.L. (1998) 'Evidence from U–Pb zircon and $^{40}Ar/^{39}Ar$ muscovite detrital mineral ages in metasandstones for movement of the Torlesse suspect terrane around the eastern margin of Gondwanaland' *Terra Nova* 10 (4) 183-189.

Two Torlesse subterranes are recognised and in the South Island both have wide extent. The older Torlesse-Rakaia terrane rocks, when unmetamorphosed are the major source of quality aggregate in the South Island although most are supplied from gravels. The Torlesse-Pahau, the youngest of the greywacke terranes, has a mixed provenance being derived in part from erosion of the older Torlesse - Rakaia terrane with additional material derived from coeval andesitic volcanism. The sediments of the Pahau terrane are described as largely indurated thin-to-medium bedded and commonly graded quartzofeldspathic sandstones and mudstones with occasional thick-bedded sandstone sequences. Locally limestones, basalts, and conglomerates have also been mapped. The two Torlesse subterranes are separated by the Esk Head belt which is largely a melange containing material from both terranes plus additional exotic material. The Pahau terrane is most extensive in the northern eastern part of the South Island where it outcrops over a large part of Marlborough. The Wairau River, which flows along the path of the Alpine Fault in the Blenheim area, separates Pahau terrane from the Caples-type greywackes, semischists and schists of the Picton - Marlborough Sounds area. From the Wairau River, the Pahau terrane extends south through the Kaikoura mountains into North Canterbury where its southernmost outcrop is just north of Waipara.

The metamorphic grade of the Pahau rocks ranges from zeolite facies to prehnite pumpellyite facies. There seems to be no systematic mapable distribution of these metamorphic zones although this may simply be the result of the poor state of geological knowledge Pahau terrane rocks in the Kaikoura ranges. The ‘z’ indicators on FIGURE 5 show where zeolites have been identified in the matrix of the sediments. The metamorphic temperature range of Pahau rocks is lower than that of the Rakaia terrane which does not contain zeolites in the matrices of the greywackes and most commonly its lowest grade is prehnite pumpellite facies which increases into low-grade greenschist before the rocks become foliated (semischists) then progress into schists and into amphibolites.

Murihiku Terrane The Murihiku greywackes are dominantly volcaniclastic. The nature of the volcanic debris can be fragments of crystalline andesitic or other volcanic rock and/or vitric (glassy material = tuffs) which is quickly chilled glassy lava. They also commonly contain angular grains of plagioclase feldspar that are part of the debris broken out of andesitic volcanic rocks and shed into the accumulating sediments. Volcanic glass alters quickly to form smectites and zeolites so the Murihiku greywacke rocks are noted for the abundance of zeolites, most commonly calcium-rich (heulandites and laumontite). Many of the sediments are shallow water and have probably been deposited close to the source of the volcanic rocks. Conglomerates, tend to be common in some areas. Volcaniclastic greywackes in the east Nelson and southern part of the South Island are different in terms of their level of alteration (metamorphism) but consistently contain chlorite in the clay matrix of unweathered rocks and in weakly diagentically altered rock they will have smectites.

Caples Terrane

Caples terrane rocks outcrop in the Southland – South Otago areas on the north side of a major fault that runs from near Balclutha to Lumsden and then turns northward to wedge out against the Alpine fault (FIGURE 1). Caples rocks in this area are generally prehnite pumpellyite facies in their lowest metamorphic grade and thus lack swelling clays but they develop schistocity, reach greenschist facies and merge into what are known as Otago Schist east of Lake Wakatipu. Caples terrane rocks also occur in the Marlborough Sounds where they are always prehnite-pumpellite facies although they do develop foliation.

Dun Mountain - Maitai Terrane

The most notable feature of this terrane is the ultrabasic (very magnesium –rich and alkali and silica-poor) rock often associated with serpentine. These rocks lack important plant nutriments so their outcrops are notably covered with stunted vegetation. Associated with these rocks and faulted into them are sequences of iron-rich sedimentary rocks (often oxidised) and sometime finely banded laminated sedimentary rocks that have strong mafic component (Lee River. The rocks are usually pp-facied or greenschist but locally may contain lawsonite.

Brook Street Terrane

The Brook Street terrane rocks are largely Permian in age and are dominated by volcaniclastic sediments including breccias, volcanic rocks with local limestones. In the Southland area the terrane includes the gabbros of the Bluff area. In the Southland rocks are frequently zeolitised while in the Nelson area these rocks are usually prehnite pumpellyite and greenschist facies.

Greenland Group (Buller Terrane)

The Greenland Group is intermittently exposed along the West Coast. The limited amount of information currently available for the Greenland group greywackes suggest they are products of erosion of quartz-rich rocks (they generally contain > 70% wt % SiO2). They also have high K2O contents (> Na2O) and variable but significant calcium contents. Unlike the greywackes of the Eastern Province, many of the Greenland Group greywackes contain carbonate.[7] The Greenland Group sequences are not known to contain either prehnite or pumpellyite; generally they are chlorite and mica-rich (muscovite and biotite) and thus belong to the greenschist facies (i.e. they will not contain swelling clays). However these greywackes have not crystallised under high stress regimes so they do not have the schistocity / foliation that characterises most of the greenschist facies rocks of the Eastern Province. From available evidence it appears that the greywackes of the Western province have experienced a higher geothermal gradient path than those of the Eastern Province.[8]

6. QUARRIED GREYWACKE AGGREGATES

In spite of the fact that greywackes constitute very large areas of the South Island there are every few quarries in greywacke. This is probably because the gravels form a more easily extracted and thus a cheaper resource. The map below which shows greywacke source rocks in terms of their strength (i.e. crushing resistance) and what may be expected in their clay mineral content, particularly their swelling clay content as represented by their clay indices. In contrast to the Torlesse, the other greywacke types in the Eastern Province are largely volcaniclastic and contain debris derived from the contemporaneous volcanism adjacent to their site of deposition of the sediments and they are much more variable in terms of their chemistry and mineral content. The major variations relate to the amount and type of volcanic material (i.e. basic, andesitic, or felsic) contained in the sediment although they all have lower silica, higher aluminium, iron and magnesium and usually also higher calcium contents, in comparison with the Torlesse greywackes. The matrices of volcaniclastic sandstones contain chlorite and have a propensity, when the rocks have only been low-temperature altered, to contain smectite.

[7] Roser, B.P., Cooper, R.A., Nathan, S., and Tulloch, A.J. (1996) 'Reconnaissance sandstone geochemistry, provenance and tectonic setting of the lower Paleozoic terranes of the West Coast and Nelson, New Zealand'. *New Zealand Journal of Geology and Geophysics*, 39:1, 1-16. Also Mortimer, N. et al. 'Regional Metamorphism of the Early Palaeozoic Greenland Group, South Westland, New Zealand'. *New Zealand Journal of Geology and Geophysics*, 56:1,2013, 1-15.

[8] N. Mortimer, S. Nathan, R.Jongens, Y. Kawachi, C. Ryland, A.F. Coper, M.Stewart and S. Randall. (2013) Regional metamorphism of the Early Palaeozoic Greenland Group, South Westland, New Zealand. *New Zealand Journal of Geology and Geophysics* 56 (1) 1-15.

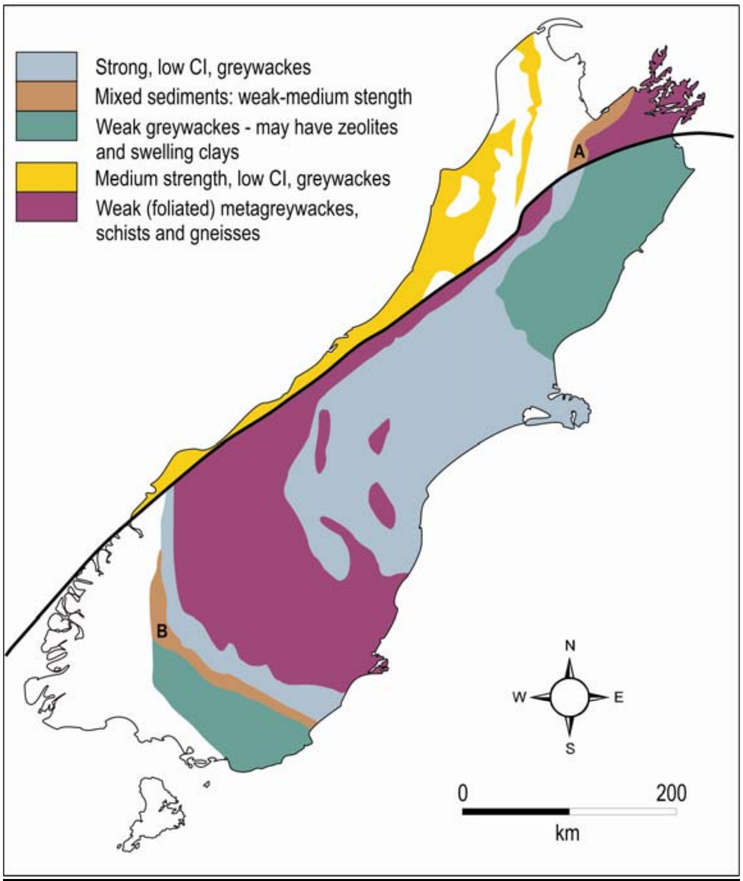


FIGURE 6 : Map showing the distribution of greywacke type and differences in their strength and some other properties that are important to aggregate industry. There are two significant areas of mixed rocks – near Nelson (A) and in Southland (B). In the Nelson area there is a compressed sequence which contains rocks of widely variable nature and strength – but none of them contain zeolites or swelling clay minerals. In the Southland areas the rocks, although being equivalent to those in Nelson may contain zeolites (laumontite) and smectites or prehnite-pumpellyite facies assemblages. The uncoloured areas are dominated by low-medium strength granites and other plutonic rocks (NW Nelson) or by gabbros and massive medium strength high grade metamorphic rocks (Fiordland and southernmost Southland).

Occasional quarries are located in the older Torlesse Rakaia terrane. Small quarries are also located in the younger Torlesse Pahau terrane, particularly in the Blenheim area where they largely produce aggregate for fill and environmental protection. The Pahau terrane greywackes ares very variable in terms of rock types and in their degree of metamorphism. In some areas the greywackes are zeolite facies (and contain laumontite in the rock) but elsewhere they have prehnite-pumpellyite assemblages.

In Southland unfoliated Caples terrane greywackes belonging to the prehnite – pumpellyite facies are quarried in the Balclutha area and produce quality aggregate but elsewhere in the Otago district much of the Caples is foliated (semischist to schist) and not used for roading or concrete aggregate.

Brook Street terrane sediments have been quarried but many of these quarries are small and ephemeral. In Southland Brook Street terrane sediments range from zeolite to prehnite pumpellyite. South of Nelson city there are several quarries in Brook Street terrane metasediments. In the other areas where quarries operate the rocks being quarried are prehnite- pumpellyite facies or low grade unfoliated greenschists including lenses of gabbro and amphibolites (Dun Mountain complex rocks).

There are several small hard-rock quarries providing rip–rap for river edge protection south of Paringa.

In the South Island, Murihiku–type greywackes are exposed over a significant area, but these rocks are generally low strength because of issues related to the presence in these rocks of the swelling zeolite (laumontite) and swelling clays, and the fact that there are much better quality rocks available nearby. Thus the Murihiku greywackes are not regarded as a significant source of aggregate and generally not used for roading or in concrete manufacture. However, local horizons of conglomerate may provide appropriately tough material to be used as roading aggregate.

7. IGNEOUS ROCKS

The South Island contains two large Miocene volcanic complexes, one centred on Banks Peninsula (11 – 5.8Ma BP) and the other in the Dunedin –East Otago area (10-13Ma BP). Volcanic rocks in these complexes are more alkaline than those of similar age and size in the North Island. These rocks (known as trachytes and phonolites) are a significant aggregate resource which has been (and still is being) quarried, although mainly in the Otago area where, because of the schistose (weak) nature of the local basement rocks the volcanics are the only significant source of quality aggregate. Many small intrusions of similar volcanic rocks scattered throughout East Otago and South Canterbury have been quarried to provide aggregate for local construction projects and building stone.

Intrusive alkaline igneous rock complexes of Cretaceous age occur in the Kaikoura Ranges[9]. While these igneous complexes are remote, and have never been quarried, they shed erosion debris into the major river systems north of Kaikoura and are a notable part of the gravels harvested from the Clarence, Awatere and Wairau River systems.

7.1 Basaltic Volcanics

While the North Island geology is dominated by Tertiary to Recent (15 – active MaBP) volcanic rocks (andesites, basalts and dacites), in the South Island there are only two major volcanic centres and they are both alkaline basaltic complexes :

1. East Otago alkaline basaltic province - continental intra plate basalts erupted from 20 to 12 maBP– two major quarries basalts have minor smectite clays and zeolite. Additionally many small plugs and dykes all over E Otago that have been quarried. Almost every basalt in South Canterbury / Otago region has been worked at some time – but most are now inactive
2. Banks Peninsula two overlapping slightly alkaline basaltic volcanoes, Lyttleton and Akaroa, rocks erupted 12 - 6 MaBP. Although there have been substantial quarries in the past – only a few are now working. A large quarry at Port Lyttleton produces material for environmental protection.

Most of the basaltic rocks contain zeolites in cavities but the swelling zeolite (laumontite) is unknown in these volcanic rocks.

The Cretaceous intrusive and rare volcanic rocks found in the South Island also may contain zeolites but again – as in the case of the Miocene volcanic centres, the zeolites are not the calcic swelling zeolite (ie laumontite). All these rocks would be medium strength and have low clay indices.

7.2 Plutonic Rocks

The South Island has significant areas of old (> 100 MaBP) granitic and basic plutonic igneous rocks (diorites and gabbros) that are not found in the North Island. Basic and ultramafic rocks are also a significant component of the Dun Mountain – Maitai terrane. Such rocks although hard and massive

[9] These rocks have been dated, using various methods, as to be 96 -97 Ma BP. M.S. Rattenbury, M.S., Townsend,D.B., Johnston, M.R. (compilers) 2006: *Geology of the Kaikoura area*. Institute of Geological and Nuclear Sciences 1:250 000 Geological Map 13, 1 sheet +70p, pp 34-35.

in outcrop are medium strength (in terms of crushing resistance). In the case of the granites – their high mica content makes their use either in concrete-making or roading problematic because of the high plasticity the mica imparts to fines.

Mafic/Ultramafic Plutonics are sourced mainly from Dun-mountain terrane. There is one small active quarry in upper Wairau Valley (Marlborough). In Southland the Bluff pluton near Invercargill has been quarried and dunite from Greenhills Ultramafic complex.

8. LIMESTONES AND OTHER CARBONATES

Limestones/Marbles/Dolomites

Most are used for environmental protection as carbonates have low strength. Limestone is soluble in water, thus they do not travel well and never form a significant component of river gravels.

Dolomites and marbles are mainly sourced from quarries in the Takaka Terrane which forms the ranges behind Motueka and Collingwood.

There are a number of quarries in the Tertiary limestones of the Golden Bay area, North Canterbury and on the West Coast. These mainly provide material for environmental protection work and/or cement manufacture.

9. GRAVELS AS SOURCES OF AGGREGATE

9.1 General Distribution

Most of the aggregate used in the South Island for roading and the manufacture of concrete is produced from gravels either harvested from active river systems or from pits in alluvial terraces, and occasionally also from beaches. Each of the different types of gravels have different physical properties, such as degrees of angularity, shapes and sizes, of individual cobbles, and the cleaness of the deposit. Gravel horizons are usually associated with other associated deposits (e.g. loess, silt horizons, peats) that reflect and indeed are characteristic of their environment of deposition.

Aggregates produced from gravels have the advantage of lower production costs, compared with those produced by hard-rock quarrying. Rivers also beneficiate the material they carry, reducing and then eliminating weak rocks and those that have low durability – delivering a material that is very significantly improved in quality compared with that of the parent rock. However, gravels do have disadvantages. In particularly they present material with limited size ranges and in many cases a mixture of rock types with very different physical properties. In the case of aggregate to be used for roading, crushed gravels often produce chips with insufficient broken faces to meet specifications.

Only in the greater Canterbury plains area are gravels composed of one greywacke type, the Rakaia – Torlesse type. Elsewhere gravels are mixtures and sometimes very complex mixtures. The most complex being in the northern-most and the south eastern parts of the South Island where the larger rivers carry material sourced from several different terranes and rocks that have been subjected to a variety of metamorphic conditions.

A topographic map of the South Island (FIGURE 7) shows many depressions - particularly in the Central Otago and Alpine areas, of glacial origin and wide glacial valleys which are the headwaters of many large river systems. Gravels of many different origins and types have been and are still being used as sources of aggregate:– gravels from braided river systems; beach gravels; terrace gravels , glacial moraines, and anthropogenic deposits (relics of the extensive sluicing gold mining in the late nineteenth century).

The strain effects generated by the horizontal movement along the active plate alpine fault boundary have produced major fracture zones and splinter faults in shallow crustal rocks. Fault angle depressions and structural basins associated with these are infilled with gravel and other deposits.

Extensive glaciation covered much of the South Island at various time during the past 2.5 million years. Three major glacial period were each followed by a warming and glacial retreat during which glacial moraine debris was reworked by river systems and carried out to the sea. The lakes located intermittently in the area from Fiordland through the Queenstown –Lakes District north into the Mackenzie Country are the sites of Quaternary glaciers now infilled by lakes and glacial deposits some of which are extensive. These deposits would later be reworked by rivers and redeposited in gravel fans covering large areas of central Otago. Thus gavels show variable degrees of cleanness, cobble sizes, and contain horizons of clay and silt, or loess (glacial rock flour which has been redeposited by winds during the arid conditions that accompany glaciations).

The South Island has many long rivers (fifteen with lengths greater than 100 km, including six longer than 200km). Most of these large rivers have headwaters in the main divide, where the rocks are generally Rakaia type greywacke, very weakly metamorphosed in the north and metamorphosed to schists or gneisses south of Gray River, and flow eastward to the Pacific coast. These eastward flowing rivers often pass through a range of other terranes and rock types. In contrast the rivers that flow westward from the main divide, and glacial moraines and gravels west of the Southern Alps contain metamorphosed Torlesse Rakaia terrane material.

The river system's bedrock exerts a strong influence on the nature and quality of gravels as far as their usefulness for aggregate production is concerned.

In the South Island the highest quality greywacke aggregate comes from river systems that that have catchment areas almost entirely in areas of unfoliated (ie non-schistose) Rakaia (Torlesse greywackes) or Caples (volcaniclastic) greywacke sandstones. These greywackes have prehnite-pumpellite facies mineral assemblages, thus they have been heated to temperatures above the stability range of swelling clays and zeolites and they also have high strength.

Gravels dominantly composed of Torlesse (Rakaia) type sandstone are found only in the Canterbury area, and on the west coast south of the Grey River where the rivers disgorging on the west coast are sourced in unfoliated Rakaia-Torlesse. The strength differential between the Rakaia-Torlesse and the other greywacke types is exemplified by the gravels in major rivers north of Kaikoura (Awatere and Clarence Rivers in particular) which contain significant material that the rivers have intersected in their westernmost headwaters and transported more than one hundred kilometres out to the coast where, the Rakaia -Torlesse material frequently constitutes pebble sizes sufficiently large to be crushed and used for roading although there may be troubles with obtaining broken faces. Canterbury area gravels are almost entirely composed of Rakaia – Torlesse greywackes which produce a top quality aggregate with high crushing resistance. The only problem associated with these rocks is that they are mica-rich and may sometimes have slightly high plasticity values, although they almost always have low Clay Indices. Weathering of the micas produces hydromicas (also known as vermiculite).

Most South Island river systems, however, contained mixed source gravels. The map below, shows the geographic distribution of different mixed-rock gravel types.

FIGURE 7 : Gravel types of South Island. Note that while there are some large areas of mixed type gravels (indicated by hachuring) there are also major river systems (and adjacent terrace gravels) that have characteristic mixtures of rocks. These are indicated by numbers 1 to 7; descriptions are provided in the text below.

The main geographic areas of the gravels of mixed rock-types are :

North Westland and Motueka -NW Nelson area. Granites are a major component of these gravels, but a variety of other rock types are also significant components. These additional components include Greenland group greywackes, marbles, and variety of metamorphic rocks. Most of the metamorphic rocks in the gravels are greenschist facies or amphibolites so swelling clays will be absent. In the Golden Bay area the river gravels contain mixed material that include sediments of low-greenschist facies (some of which is Greenland group material), granites, gabbros and amphibolites. In some areas of northern Westland river systems opening to the Tasman Sea have their headwaters in weakly foliated or unfoliated Rakaia terrane and can have high strength. The high mica content of those mixed gravels that contain granites may provide problems if aggregate derived from them is to be used for roading and for concrete making. Weathering of the micas produces hydromicas (also known as vermiculite) which have some swelling capacity.

Central Otago and West Canterbury-Alpine area. The greywacke resources of the Otago area have all been metamorphosed and are foliated and converted to strongly schistose rocks. Most commonly the source rocks are quartzofeldspathic (and micaceous) Otago schists (north and east of Queenstown) or volcaniclastic Caples schists (chorite- and amphibole-rich) west of Lake Wakitipu and south of Queenstown. Most quality aggregate comes from the natural beneficiation provided by river systems which produce quartz enriched gravels.

Fiordland area. In the Fiordland area there are significant resources of high grade unfoliated granulites and gabbros – which would produce median strength but otherwise quality aggregates. These rocks tend to be coarse grained and massive, lack clay minerals but because they are dominated mineralogically by pyroxenes and feldspars they will not be high strength (although they are on the high end of medium strength).

River systems in other areas produce gravels which have characteristic mixed-rock compositions.

The Waimea River (1, in Figure 7) has a variety of source rocks in its headwaters and the gravels contain debris that ranges from weak to relatively strong and with a variety of different metamorphic grades. Debris contained in these gravels has been derived from Brook Street terrane volcaniclastic sandstones, Dun-Mountain Maitai terrane prehnite-pumpellyite metasediments, with contributions from granites and gabbroic rocks exposed in its western headwaters.

The Wairau River (2, in Figure 7) contains mixed schistose and semischistose rocks (originating from Caples and Torlesse-terrane greywackes on the north side of the Wairau River), diagenetically altered Pahau terrane greywackes (zeolitised and with swelling clays – from the south side of the river) minor amounts of gabbroic and mafic material from the Dun Mountain – Red Hills area (exposed in the river near at the Wash Bridge). In the upper reaches of the river where the Wairau runs from south to north it intersects some Rakaia –Torlesse. There are also small amounts of volcanic rock derived from the Kaikoura Cretaceous intrusive complexes entering the river systems and appearing in the gravels.

In the Kaikoura area (3, in Figure 7), the Awatere and Clarence River gravels are largely composed of diagenetically altered Pahau terrane greywackes (some of which might contain laumontite), high strength Rakaia-Torlesse terrane rocks sourced from the extreme western headwaters of the rivers, and erosional debris from the local basalts in the Pahau and the intrusive alkaline rock complexes in the Kaikoura ranges.

In the South-west Otago - Southland region (4, in Figure 7), rivers have headwaters in schistose Caples type greywackes. Gravels contain mixtures of greywacke, schists, weakly metamorphosed Caples and volcanic rocks derived from the Murikiku and/or or Brook Street Volcanics.

Gravels from the Mataura river in Southland (5, in Figure 7) contain debris derived from the Brook Street intrusives, Dun Moutain-Maitai terrane, and the Murihiku terrane (greywackes and volcanics). The Oreti River contains large amounts of debris from the Murihiku terrane.

The Aparima River in south-west Southland (6, in Figure 7) contains Brook Street terrane and some gabbroic material. Rivers further to the west contain progressively more massive granulitic material derived from the Fiordland complexes.

Along the Westland coast (7 - in Figure 7) most aggregates are produced from river and beach gravels largely derived from the mica schists along the Southern Alps. None produce high strength material.

9.2 Issues related to mixed-source gravels

Gravels always present some challenges to those who produce roading aggregate from them. Some of those challenges have obvious causes – for example the limitations that the gravel size imposes, which may make it difficult for the aggregate to meet the broken face requirements, and large crystals of feldspar in some types of volcanic rocks and fine-grained rocks with river-polished smooth surfaces often do not adhere well to bitumen.

While the individual components of the South Island's mixed gravels may be common quarried source rocks overseas (particularly in old continental countries) and thus have well documented physical properties and performance histories, such records do not exist for the dolomites, marbles, gneisses, granulites, granites, and other plutonic igneous rocks (gabbros and ultramafics) that are components of the South Island's gravels.

Individual components of mixed source gravels have their own matrix of physical properties. Important physical properties such as crushing resistance (uniaxial compressive strength), resistance to abrasion, surface texture and chip shape are rock-type dependant with ranges in values that are also rock-specific. Granites, mica schists and marbles are generally at the low end of the strength and resistance to abrasion spectrum; igneous rocks gneisses and granulites in the mid range, and quartzites and quartz-rich strongly lithified sandstones sandstones such as Rakaia –type Torlesses greywackes (the latter often described in overseas literature as "gritstones") at the top end of the strength / resistance to abrasion spectrum.

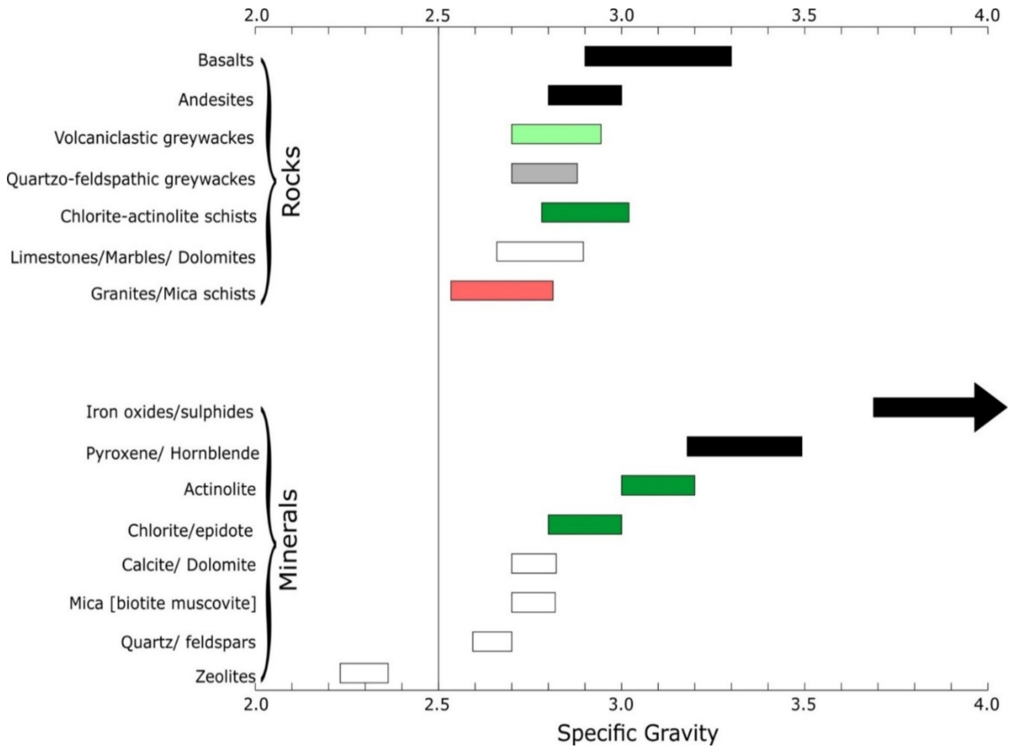


FIGURE 8 : Variations in specific gravity (relative density) of common rocks and the minerals they contain. Colour is a good indicator of density. Light coloured rocks have low density. Dark coloured rocks usually have high density

A rock's density is determined by its constituent minerals (their nature and volume percentage) and the porosity of the material. Rocks rich in quartz and feldspar (such as the quartzofeldspathic Torlesse type greywackes, mica schists and granites), always have low specific gravities (in the range 2.6-2.7) although they have significantly different strengths and fragment shapes. Volcaniclastic greywackes and most feldspathic volcanic rocks have higher densities (2.7 - 3.0), while amphibole and pyroxene -rich igneous and metamorphic rocks usually have densities in excess of 3 but all have medium strengths. Shapes of particles of different rock types may also differ due to flow orientation of minerals (in volcanic rocks) or mineral segregations / banding due to metamorphic processes.

Segregation of particles on the basis of grain size during handling and stockpiling can be a significant issue in the aggregate and mineral industries, even when only one material is involved, but it is exacerbated when the material is composed of a mix of materials with different densities and grainsizes. In mineral processing it is common to separate different materials on the basis of their grainsize and/or densities using, sieving, shaking tables, riffles and cones; basic methods that are also used in processing aggregates.

Photo Plate 2 : Raw "feed" stockpile of river gravels, Nelson district. Photo is taken from the base of the stockpile looking towards the top. The stockpile has been formed by tipping material onto the top of the pile causing the grainsize segregation of cobbles as they fall down the stockpile. Note also the variation in shape of cobbles – from platey to rounded. (Photo Kyle Paddon)

Particular care should be taken to minimise segregation when processing, handling and transporting well-graded mixed-source aggregate as it is during these operations that particle size, density and rock-type segregations can most easily occur[10]. Most of the precautionary measures are well documented, often simple and low-cost, and current good practice for most large operations, but when stockpiles of graded material are left standing for long periods or poorly "sampled" for final use, segregation issues may occur[11].

Density differences of particles in multicomponent systems will also affect test results – particularly those many tests used to specify aggregates that rely on determining the weights of different size fractions (e.g. grading envelopes and sand equivalent tests), or increases in the weight of sieve size

[10] O'Flaherty, C.A. (ed) *Highways. The location, design, construction and maintenance of pavements* (4th Edition) 2002, 142-153.
[11] Barksdale, Richard D. (Ed) *The Aggregate Handbook*. (US National Stone Association, 1991) 8.42.

fractions after testing (for crushing and abrasion indices, and the weathering quality index). While some of these variations may be trivial, they do affect the test results and thus negate any direct comparisons between data sets of different aggregate types.

While the weighted average of the physical properties of individual components may provide an acceptable matrix of data for the bulk sample, the inherent differences in strength and density of different components provide opportunities for rock-type segregation into different size fractions of the aggregate. Thus an aggregate that meets specification may, and often does, contain components which are much less durable than desired, and specified by the consumer.

When there are different materials with different densities involved, the individual components will readily segregate during handling and stockpiling and laying of aggregate. Segregation of low density, low strength components from an otherwise conforming - to - specification aggregate will provide potential sites of failure.

Many texts publish tables of such data for their national range of aggregate source rocks[12] New Zealand has no such compilation or historic record of properties and performance histories of its aggregate source rocks.

[12] (e.g. O'Flaherty, 2002 for UK roading materials, and the National Stone Association's "Aggregate Handbook" for North American materials).