

# Residual Rock Bursting in the Homer Tunnel, Fiordland N.Z.

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**SUMMARY** Explosive rock spalling following the excavation of the Homer Tunnel in 1953 required urgent analysis and remedial measures before public use of the tunnel was possible. The bursts were confined to areas of strong massive brittle rock located between zones of shearing and jointing. Residual stress locked in from past geological events and released by the excavation of the tunnel was assessed as the probable cause, and the rapid elimination of spalling and of rock falls over four years appeared to confirm that judgement.

The tunnel is located in an area where unusual geological events have occurred in comparatively recent time, including massive offsetting and uplift exposing deep seated crustal rocks. The stresses causing the problem are considered to have been the resultant of the uplift and the erosion of some 18kms of rock in the last 6 Million years which has left high horizontal stresses locked in while the vertical component has decreased in accordance with the present overburden thickness.

## 1. INTRODUCTION

The Homer Tunnel was constructed by the N.Z. Public Works Department (PWD) between 1934 and 1953 to give road access to Milford Sound. The country between Lake Te Anau and the Sound is rugged and mountainous with peaks between 1520m and 2740m with their lower slopes covered with dense bush. Profound glacial valleys up to 800m deep, now occupied by rivers, provide the route for the highway except at the divide where the Homer Tunnel penetrates a razorback ridge formed by glacial cirques between the Upper Hollyford and Cleddau valleys (Figure 1). The east or Homer portal (914m RL) was located well above the valley floor to reduce the length through bouldery scree, and the tunnel descends at a grade of 1 in 10 to the Cleddau portal, a distance of 1275.4m. Because of the lack of wharf facilities at Milford and the inaccessibility of the western portal, the tunnel was driven downgrade from the east. No seepage problems were expected. The two-way road tunnel was designed as a semi circular section 7.31m in diameter with the centre 1.52m above floor level.

## 2. HISTORY OF CONSTRUCTION

Details of the tunnel and the early stages of construction of a pilot heading are given in a paper by White (1947), and aspects of the enlargement are discussed by Hart (1952) and by Downer (1977). The full story of the tunnel construction and the numerous vicissitudes that occurred from water entry, isolation by snowfall, dry snow avalanches, (described in a classical paper by Smith, (1947), and from rock spalling constitutes a saga

that remains to be written.

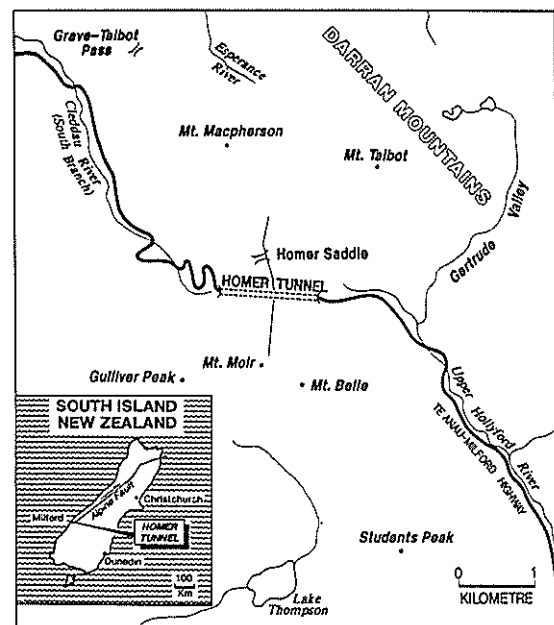


Figure 1 Locality Plan

The following is a summary of the progress of construction:-

- Dec, 1934 Pick and shovel work at Homer Portal.
- Jun, 1936 Rock excavation started with heading and bench.
- May, 1937 Fatalities from dry snow avalanche, work ceased, 143m completed.
- Nov, 1937 Downer & Co. started bottom

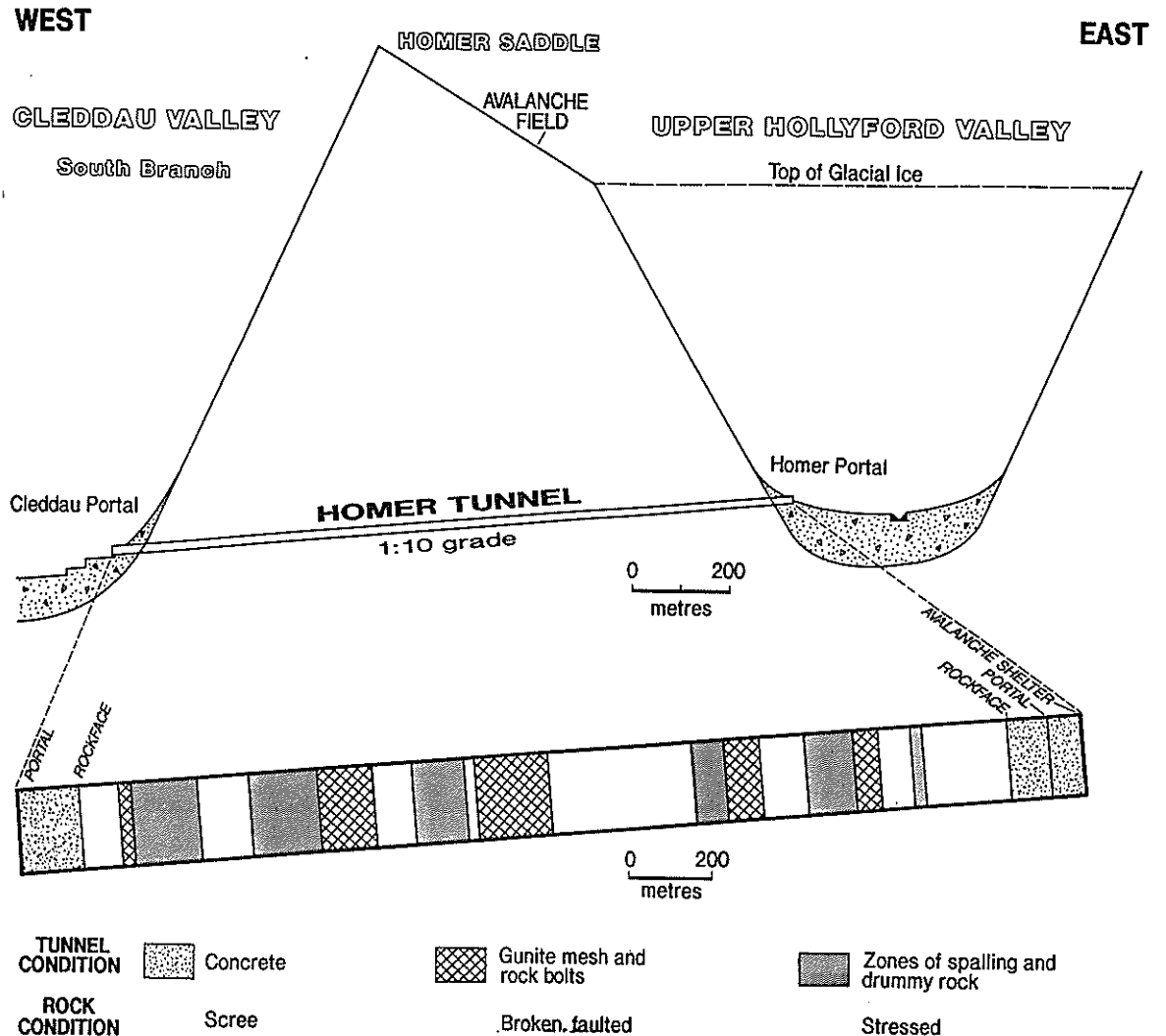


Figure 2 Long section showing rock and tunnel conditions

- Mar 1940 heading (3.96m x 2.7m). Cleddau scree penetrated, enlargement started.
- Mar 1941 Ring drilling, 18 holes per ring, 0.76m apart.
- Mar, 1942 Work suspended "for the duration".
- Mar, 1951 Enlargement recommenced by Downer & Co. Rock spalling.
- 1953 Work completed.
- 1954 Tunnel opened to public, with winter closures.
- 1984 Closures minimized, avalanche warning system.

### 3. GEOLOGY

The Homer Tunnel is located in the rugged Darran Mountains which are formed of the Darran Complex of leucograbbro, norite, granite, and diorite. The tunnel itself is driven in a brown biotite norite, (biotite leucogabbronorite) which often exhibits a rudely gneissoid structure, and has cataclastic properties with internal evidence of compressive stress.

Numerous vertical pegmatite veins or dykes striking southwesterly and occupying tensional rents are present in the tunnel. Small dykes of dark green hornblende also occur.

The Darran Complex shows extensive areas of intrusive breccia, where new magma has invaded and split up and shattered older rock, then cooled and solidified only to be invaded and split up again. (Blattner & Coates, 1989). The igneous complex was formed between 230 and 100 million years ago beneath the continental margin of Gondwana. Late Cenozoic deformation has affected the area with horizontal offsetting of 480 kms on the Alpine Fault, and in the last 6,000,000 years the area has been gradually uplifted by some 18km, with an equivalent amount of erosion (Suggate, 1963). The last major geological event, some 20,000 years ago was glaciation, with a reshaping of the land and the emplacement of glaciers upto 800m deep. Melting of the ice occurred during the Last Interglacial, 18,000 to

13,000 years before present.

Significant tectonism and seismicity is still occurring associated with the Alpine Fault some 30kms northwestwards of the tunnel.

#### 4. ENGINEERING GEOLOGY

##### 4.1 Groundwater

Because the tunnel is some 400-460m below the Homer Saddle, it was not expected that there would be any problems with water. However slow water seepage was encountered along most of the length of the tunnel with flows contained in shears or faults several places, with two strong inflows of up to 7.6 l/s.

##### 4.2 Jointing and Stability

Jointing in the tunnel walls is variable, with some massive areas devoid of joints, and other zones of close jointing, shearing and faulting in places giving zones of soft fault breccia. Several areas of horizontally jointed rock were met where roof slabbing was dangerous and required support, and timbering had to be used over about 30m of the pilot heading. The full tunnel section contained five main zones of rock breakage over about 210m where remedial works in the form of gunite, mesh and bolts had to be installed (Figure 2). The rock at the Cleddau end, over about 80m was notably weaker and more broken by jointing than elsewhere (White, 1947).

##### 4.3 Rock Spalling in the Heading

The pilot heading encountered several zones where the rock was obviously under stress. Spalling of the rock took place with a crack like a rifle, and fragments were shot across the tunnel with considerable velocity. These effects were observed immediately following rock excavation. (White, 1947)

##### 4.4 Problems during Tunnel Enlargement

During tunnel enlargement, the strain bursts usually began soon after a round was blasted although in some instances the explosive spalling held off for several hours, or longer (Hart, 1952). Once started, noise and spalling continued for an hour or two, and then became quiescent. In some areas periods of activity occurred several weeks after blasting and excavation had been completed. In other areas quiet spalling producing onion skins of rock occurred with the slabs falling either singly or in mass. In these areas the roof shape tended to assume the shape of an acute arch with the apex of the arch gradually getting higher as spalling continued. (Hart, 1952)

Immediately a slab spalled off, the underlying rock face was smooth and solid, yet a few hours later it sounded drummy with a new slab detaching itself, then bulging outwards, until eventually

it projected from the walls with explosive force (Figure 3). The spalled slabs were tabular and lenticular, usually of dinner plate size or larger. The edges were normally thinner than the centre, and they could not be fitted back to the spalled face as the shape had changed in response to the stresses. The inner surface of the detached slab surface was partially coated with powdered rock. (Gordon, 1953)

##### 4.5 Geotechnical Reconnaissance

A geotechnical reconnaissance of the tunnel was made in October 1953. Logging of the areas of spalling was done initially by noting areas of fresher surface in the dust-covered rock. Measurements were made of rock falls and spalls, noting the number of pieces and their size, shape and the location and position. These records were continued annually in three phases (i) at the end of the winter closure, (ii) following barring down from a mobile platform before summer opening and (iii) during summer when new falls and spalls were recorded as they were removed during maintenance. It was found that stress spalling was confined to areas of massive unjointed rock, and this applied to the locations of violent spalling that had been recorded during enlargement.

A progressive record was made of spalls, falls and drummy roof areas and this showed six areas of concentrated distress (Figure 2). These areas were up to 30m wide, and were separated by areas of jointed, faulted and sheared rock which contained the sections that had to be secured by bolting, mesh and gunite following enlargement. Parts of two of the active spalling zones in the roof were given a gunite cover immediately after excavation, and no further activity was experienced in these areas. (Hart, 1952)

The incidence of spalling from the walls and roof decreased sharply over a period of a year, and detailed monitoring was ended after four years when the spalling had practically ceased.

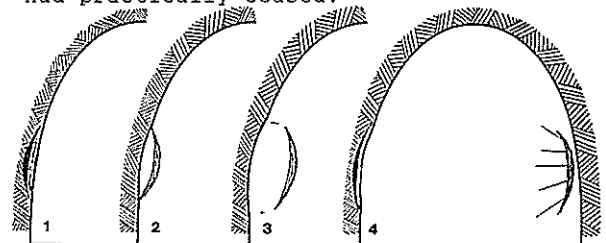


Figure 3 Explosive Rock Spalling

#### 5. EVALUATION OF GEOTECHNICAL RISK

At the completion of the enlargement of the tunnel, the P.W.D. had to face a problem of public safety if spalling continued unabated or even intermittently. Dry snow avalanches were bad enough, but they could be avoided by closing the tunnel during the winter.

Plates of rock exploding off the walls or accumulated layers falling from the roof could possibly close the tunnel for years. The long desired road access to Milford which was a political promise close to reality had to be evaluated in terms of geotechnical risk. At the time (1953) the science of rock mechanics was in its infancy, and little was known about the tectonic history and geology of the area.

An urgent consensus of ideas on cause, risk, control or avoidance was sought. Evaluations were made by the leading engineers of the P.W.D., by the District Inspector of Mines, by an experienced engineering geologist, H. E. Fyfe of NZ Geological Survey, and by the writer, who had just completed the geotechnical reconnaissance. A most hopeful sign was that the views of the two engineering geologists were similar, and this unprecedented situation along with the reasonable arguments that were presented about the possible causes lead to a quick but considered decision. Because of the isolation of the two periods of spalling in the pilot heading and in the full tunnel, and the obvious attenuation with time, residual stress release was considered to be responsible for the problem and the risk was therefore considered to be a short term one as the locked-in stresses had been largely released. Careful monitoring, inspection and continued barring-down were prescribed during the then winter closures and the tunnel was opened, as promised, to the public in 1954. Since that time there have been no major problems with spalling rock.

#### 6. SHALLOW ROCK SPALLING PHENOMENA

In the marble quarries of Vermont, USA, channelling in the faces occasionally disturbed the stresses sufficiently to produce fractures with enough violence to throw the channelling machines, weighing several tonnes off their tracks. These "grassroot" stresses were considered residual. (Bain, 1931) Similarly, in the granite quarries at Barre, Vermont, residual stresses correlated to geological pressures that had acted at the close of the Tertiary, affected the excavation of blocks. (White, 1946). At Franklin Furnace Mine (N.J.) rock bursts, at the 180m level were sufficiently powerful to overturn loaded ore cars.

Skin spalling occurred at the bottom of the excavations for foundation of the Coulee Dam, almost at ground surface. Excavation had been proceeding for some depth but no satisfactory bottom was encountered as stress relief formed another loose layer of rock - rather like the skin of an onion. C.P. Berkey on acquaintance with the problem stopped further excavation and the dam was satisfactorily founded on confined (solid) rock.

Rock spalling occurrences at the Delaware Aqueduct which was part of the New York

Water Supply Tunnels were noted at 160m beneath the surface, but trouble did not become continuous until a depth of over 300m was reached. Bird (in Bucky, 1942) has described various shallow rock spalling phenomena in the tunnel which were characterized by name - air slaking, working rock, springing rock, spalling rock, popping rock, and bursting rock, but he concluded that the occurrences were varying intensities of the same cause. The description of the Delaware Aqueduct rock bursting given by Bird is almost identical with the occurrences recorded at the Homer Tunnel.

At the New Victoria Dam Site on the Darling Scarp near Perth, Western Australia, spalling of fresh granite surfaces occurred some 3 to 6 weeks after the excavation of some 4-6m of weathered rock and overburden (Gordon, 1991). Spalling occurred only in massive areas, where the dominant rock structure was provided by sheet joints subparallel to the topography. Prominences or domes were favoured locations, and the detachment of the disc-shaped slabs was accompanied by audible noise. The stresses appear to be locked in or incipient sheet joints, released by excavation unloading.

#### 7. STRESS IN ROCK MASSES - TERMINOLOGY

The actual stress at any point in a rock mass is the resultant of the stress caused by engineering activities (Induced stress), and the stresses present in the rock mass before these activities started. The latter stresses are referred to as Natural stresses, and can be conveniently divided into four:- (i) Gravitational stress which is due to the weight of superincumbent rock, (ii) Tectonic stresses due to the active present day straining of the earths crust, (iii) Latent stress which is due to other natural causes such as swelling rocks, thermal stress, topographic stress and mineralogical stress, and (iv) Residual stress. According to Denkhaus (1967), residual stresses are systems of stress in equilibrium or approaching equilibrium in the interior of a body, resulting from the whole stress history of the region. This can include past tectonic stress, geological loading from sedimentation or volcanic activity, and unloading stresses caused by erosion or denudation or by ice melting. Residual stress systems are thus a property of the rock material. Voight (1967), used an analogy of different springs in tension and compression clamped in a common yoke, a system shown diagrammatically in Figure 4.

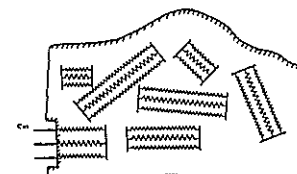


Figure 4 Residual Stress as a system of springs

Residual stress becomes important when the boundary of a stress system is cut in the course of excavation. The locked in residual stresses are released, and either gradual or violent movement occurs. Tensile straining, spitting, flaking or strain bursting at a face are manifestations of such residual energy releases.

The terminology used in this paper, illustrated in Figure 5, is expanded from that proposed by Beilenstein and Barron (1971).

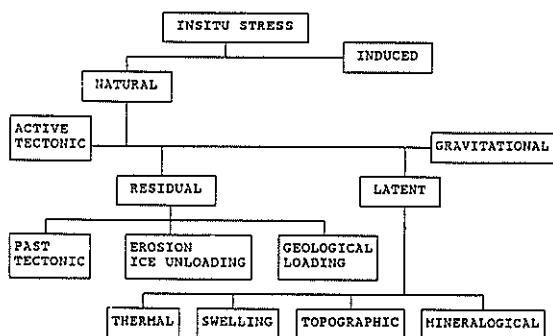


Figure 5 Terminology of Rock Stress Causes

## 8. POSSIBLE CAUSES OF SPALLING

All types of natural stress as indicated in Figure 5 were considered as being possible causes for the spalling in the Homer Tunnel:-

**8.1 Gravitational Stress.** The overburden consists of some 460m of igneous rock and seasonally the presence of snow and ice. The vertical normal stress ( $O_z$ ) is assumed to be given by the unit weight of rock ( $\gamma$ ) multiplied by the depth ( $Z$ ) below the surface.  $O_z = \gamma Z$ . The horizontal normal component of stress is given by

$$O_x = O_y = \frac{V}{1 - V} O_z \text{ where } V \text{ is Poissons ratio}$$

Rock will not fail in the walls of the tunnel until the circumferential stress becomes equal to the unconfined compressive strength of the rock. Normally the circumferential stress does not exceed twice the overburden pressure (Terzaghi, 1946).

The ratio between the horizontal pressure and the vertical load depends primarily on the geological history of the rock. Anisotropy can have a considerable influence on the size and directions of local principal in situ stresses. In a folded, eroded or intruded rock mass the horizontal pressure depends in part on whether the forces have already disappeared or whether they are still stored, as in a spring, ready to be released.

**8.2 Denudation** may reduce the vertical

stress, while the horizontal stress is reduced by a lesser amount leading to in-situ states of stress with high values of the ratio of horizontal to vertical stress, particularly at shallow depth. Voight, (1967) has presented a mechanism for unexpectedly large horizontal near-surface stress components having been locked in while the vertical component decreased as a result of denudation. An example has been given by Moye, (1959) where horizontal stress under Happy Jacks Plain in the Snowy Mountains was 10 times greater than the horizontal stress caused by the weight of the overlying rock. Such a stress is truly residual.

Suggate, (1963) estimates some 18kms of rock has been uplifted and removed by erosion in Fiordland in the last 6,000,000 years, so this mechanism is considered to be a prime candidate as the cause of the pressure problem. Several zones of horizontally jointed rock were encountered in the pilot heading where slabbing became dangerous, and roof support was urgently required.

**8.3 Active tectonism** is usually manifest by the accumulation of strain and its release through fault movement either as slippage or as faulting. The buildup process is marked by seismic events varying in size from micro earthquakes to moderate tremors. No seismic activity has been recorded as originating in the tunnel area, the nearest known active fault is the Alpine Fault some 30 kms to the northwest. Active tectonism is ongoing and regional so that the stresses causing the 1947 and 1953 spalling occurrences, if tectonic, should have been continuously active and would not be diminished or attenuated in time.

**8.4 Past tectonic stress** locked into the rock mass is a possible cause of the spalling. The current phase of activity on the Alpine Fault some 30kms to the northwest of the tunnel commenced some 20 million years ago and resulted in horizontal offsetting of 480 kms as well as vertical uplift. The area also contained many other faults active at that time. (Bishop, Blattner and Landis, 1990). Significant earthquakes now occur at about 10 year intervals.

**8.5 The last disruptive intrusions** of gabbros in the Darran Complex occurred some 100M years ago. The shattering effects of magma intrusion can be seen in the breccias in the surrounding areas and in the unhealed faults and in sheared areas in the tunnel. Residual stresses could be the result of incomplete rock breakage during these intrusions when it is safe to assume that not a single cubic metre of rock escaped compression and distortion. The rock mass round the tunnel has undoubtedly inherited some of the stress imposed on it at great depth.

When the stresses exceeded the elastic limit of the rock a break or fault occurred. As long as the elastic limit of the rock plus the confining force of

the superincumbent load could retain these forces the stresses remained quiescent. When the tunnel was excavated the unbalanced forces had somewhere to go, and rupture and spalling occurred.

8.6 Ice Melting When melting occurred of some 800m of ice occupying the Upper Hollyford and South Cleddau Valleys the removal of the weight would have a considerable effect on rock dilatancy. The unloading forces which could be as much as 13 mPa at the bottom of the valley were almost certainly expressed as sheet joints, formed subparallel to the rock surface regardless of any structural trends in the rock mass. Sheet joints decrease in incidence with depth into the rock mass, so it is possible that residual rebound stress has been locked-in where sheeting has not broken the rock mass, which could account for stressed zones within 100m of the Homer and Cleddau portals. However the zones of spalling near the middle of the tunnel, some 500m from the valleys are more difficult to accept as resulting from ice melt unloading.

8.7 Topographic stress is caused by irregular surface topography, such as the presence of a sharp notch of a V shaped valley. Stress concentrations may even approach the strength of the rock mass. Glacial valleys are reasonably uniform in shape, and free of irregularities, and topographic stresses do not seem to be relevant except for openings excavated parallel to the steep valley walls (Brekke, 1970).

## 9. CONCLUSIONS

In practical terms the search for the origin and cause of the spalling phenomena in the Homer Tunnel was only of philosophical interest to the people who constructed and maintain the facility. The questions the engineers asked in 1953 were "What are the natural stresses, what is their direction and duration?" These practical questions were only partly answered at the time but enough evidence was available to say that the stresses were residual, largely horizontal, and once released attenuated with time. Even now with almost 40 years maintenance of the tunnel backed by the knowledge of four decades of advancement in rock mechanics, and with some detailed regional geological mapping finally available, it is still difficult to answer the interesting questions as to the precise origin and causes of the rock bursting. However stresses residual from the erosion of 18km of rock are the prime candidate.

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