

# THERMO-TECTONIC HISTORY AND HYDROCARBON PROSPECTIVITY OF GREYMOUTH COALFIELD, WESTLAND, ASSESSED BY APATITE FISSION TRACK ANALYSIS

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## Abstract

The Greymouth Coalfield is contained within a large southward plunging and reverse faulted anticline in northern Westland, east of Greymouth. The basin contains a late Cretaceous through Oligocene sedimentary succession, with extensive coal seams in the Cretaceous section and in the Late Eocene Brunner Coal Measures. Stratigraphy shows that the basin had a half graben geometry, thickening eastward; the lower coal measures have therefore been differentially buried to greater depths eastward across the basin. This differential burial is reflected in progressively higher coal rank eastward across the basin.

Apatite Fission Track Analysis has been applied to samples from drillhole and outcrop samples from the Greymouth Coalfield to better understand the thermal and tectonic history, and hydrocarbon prospectivity, of the Brunner - Mt Davy anticlinorium. The results show that the maximum paleotemperatures experienced by the late Cretaceous - late Eocene coal-bearing succession sampled, increased eastward across the coalfield towards the axis of the faulted anticline, and then decreased further eastward. The Rapahoe (western) sector of the coalfield experienced temperatures ranging from 80° (coast) to 100°C (inland). Vitrinite Reflectance ( $R_o$  max %) values increase over this temperature range from 0.5 to 0.67%, and the isothermal contours estimated from the fission track data broadly parallel the trend of the vitrinite reflectance contours. Over the eastern sector of the coalfield peak temperatures reached by burial exceeded 100°C, and the fission track data identify the timing of inversion and cooling of the succession that accumulated in the Paparoa Trough. The first uplift phase extended from ~19.5 to ~15.5 Ma, and probably resulted in several hundred metres of uplift and erosion of the sedimentary succession in the Paparoa Trough. A second uplift phase occurred from ~12 to ~7 Ma, which together with a third uplift phase during the Quaternary resulted in the inversion of the Paparoa Trough. The inversion is known to have been achieved by a reversal in the sense of displacement of a normal fault zone that had controlled accumulation in the former half graben.

The early and late Miocene uplift phases of the anticline coincide with unconformities in the Neogene section of the western limb of the adjacent Grey Valley Syncline, which is common to the eastern limb of the anticline. In both of the Miocene uplift phases uplift of the western limb of the anticline continued for 1 to 2 million years after uplift of the eastern limb (western limb of syncline) stopped. This is explained by a model involving initial coupling of the fault zone and uplift on both sides of it, followed by reverse faulting of the western limb of the anticline over the eastern limb, which loaded the eastern limb and caused subsidence of the Grey Valley Trough. This episodic coupling, and loading and sedimentation is typical of foreland basin development. The early Miocene uplift phase is a manifestation of initial development of the modern plate boundary through New Zealand, and the late Miocene uplift phase coincides with the plate boundary becoming obliquely compressive.

The coal-bearing source beds experienced maximum temperatures during the late Oligocene, prior to the start of inversion. The source beds would therefore have passed through the oil formation window, and over much of the coalfield, into the zone of gas production, prior to the formation of potential trapping structures. Moreover, the degree of inversion is such that the potential reservoir beds have been deeply eroded over the coalfield, but not to the south along the trend of the plunging anticline. Although oil seeps and gas-prone horizons have been encountered, the coalfield is not considered to preserve much hydrocarbon prospectivity.

## Introduction

North of Greymouth the West Coast of the South Island is dominated by the basement-cored Paparoa Range, which marks the western margin of the West Coast basin-and-range province (Figure 1). This region is well known for its spectacular Neogene structural inversions: many of the present ranges that rise to over 1000 m above sea level, occupy the axes of linear late Cretaceous-Paleogene depocentres that contain successions up to 4 km thick, and the current basins or depressions developed over earlier structural highs (Gage, 1952; Laird, 1968; Nathan *et al.*,

1986). One of the best examples of these inversions occurs in the Greymouth Coalfield, located at the southern end of the Paparoa Range, where there has been sufficient uplift to exhume different levels of a late Cretaceous-Paleogene succession, but not enough to completely erode it away (Figure 2).

In the study reported here, we have applied the technique of apatite fission track analysis to the sedimentary section and underlying basement in the Greymouth Coalfield. Apatite fission track analysis is a new inorganic technique for analysis of low temperature thermal histories, especially those of the magnitude found in sedimentary basins (e.g. Green *et al.* 1989a). In particular, it has the potential to establish several aspects of the thermo-tectonic history of sedimentary basins.

- (i) It enables reconstruction of the maximum temperatures in the range 50-120°C experienced by sequences, and in some settings the duration of heating. This is relevant to assessment of the degree of maturation of organic matter contained within sequences.
- (ii) The technique enables establishment of the timing of cooling of sequences involved in inversion. Because cooling is usually associated with inversion, information is obtained about the timing of structure formation in relation to the timing of maturation.
- (iii) Apatite fission track analysis can establish the degree of cooling, and hence the amount of inversion, by comparison of the maximum temperatures experienced by the sequences with their modern formation temperatures.

We were attracted to apply apatite fission track analysis to the Greymouth Coalfield for several reasons.

- (i) The stratigraphic and structural setting of the coalfield is well understood. Inferences about the timing of inversion and the amount of section removed from the coalfield based on the regional geology, are available and can be compared with the interpretations drawn from the fission track data.
- (ii) There is a good coverage of vitrinite reflectance data for the coalfield, the values of which together with the stratigraphy indicate differential burial across the basin. Maximum paleotemperatures assessed by fission track analysis can potentially therefore be compared with

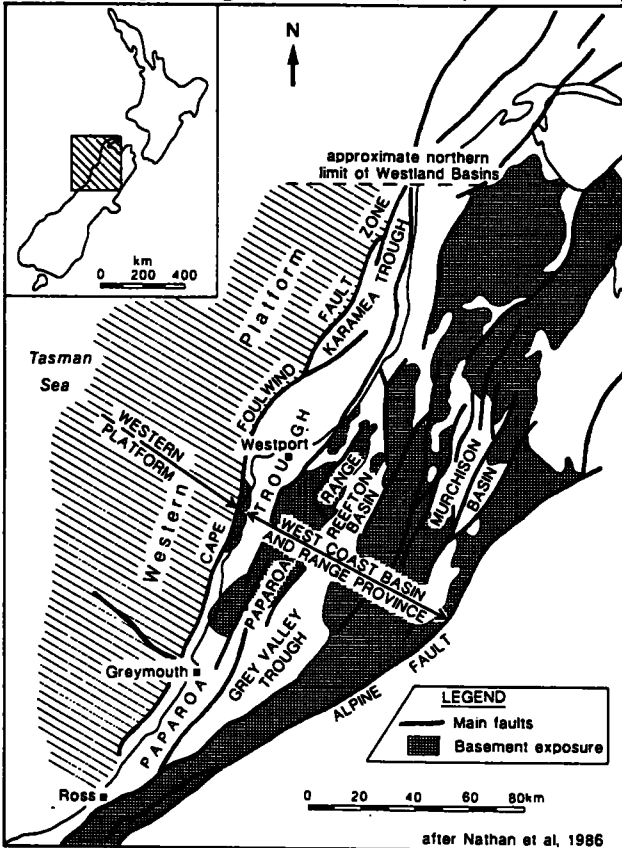


Figure 1: Simplified structural setting of West Coast, South Island. (From Geosearch (1991) *Petroleum Resources of New Zealand*. Resource Information Report 10).

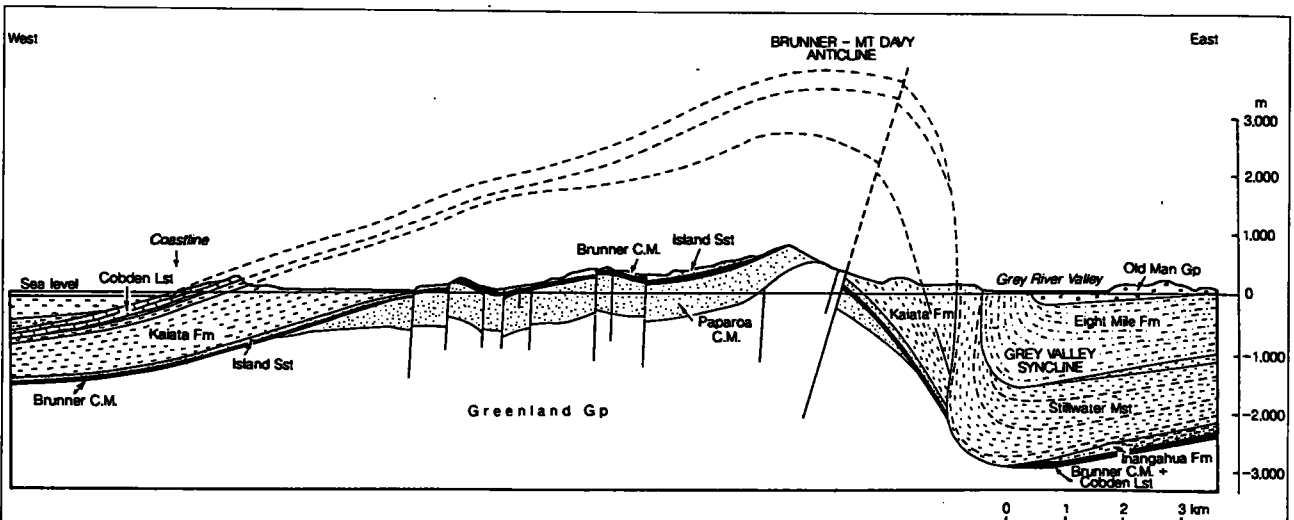


Figure 2: Cross-section through Greymouth Coalfield (modified from Nathan, 1978).

vitrinite reflectance values over a wide temperature range.

- (iii) The structural setting of the coalfield is characteristic of much of the West Coast, and new details, particularly of the timing of inversion have broader significance in terms of the regional tectonics.
- (iv) The coalfield is known to have oil seeps and gas prone horizons, and has previously been the focus of hydrocarbon exploration.

### Structural and Stratigraphic Setting

The Greymouth Coalfield lies within the west limb of a spectacular southward plunging and eroded anticlinorium (Gage, 1952; Nathan, 1978): Ordovician sedimentary basement in the core is overlain by a late Cretaceous-Paleocene non-marine coal-bearing succession up to 800 m

thick (Paparoa Coal Measures), a thin Middle Eocene coal-bearing sequence (Brunner Coal Measures), and a late Eocene-Oligocene marine succession several kilometres thick (Figure 3). The principal structure is the plunging and asymmetrical Brunner-Mt Davy Anticline. North of the Grey River the crest of this structure is eroded to the level of the Paparoa Coal Measures and the axis is marked by several *en echelon* reverse faults, downthrown to the east. Further north, basement climbs to over 1000 m above sea level, whereas south of the Grey River structurally conformable late Eocene and Oligocene sediments form the nose of the anticline. The more gently dipping western limb of the anticline contains numerous NNE-trending normal faults with throws of 15-150 m that do not greatly interrupt the simple structure of the west dipping succession (Gage, 1952).

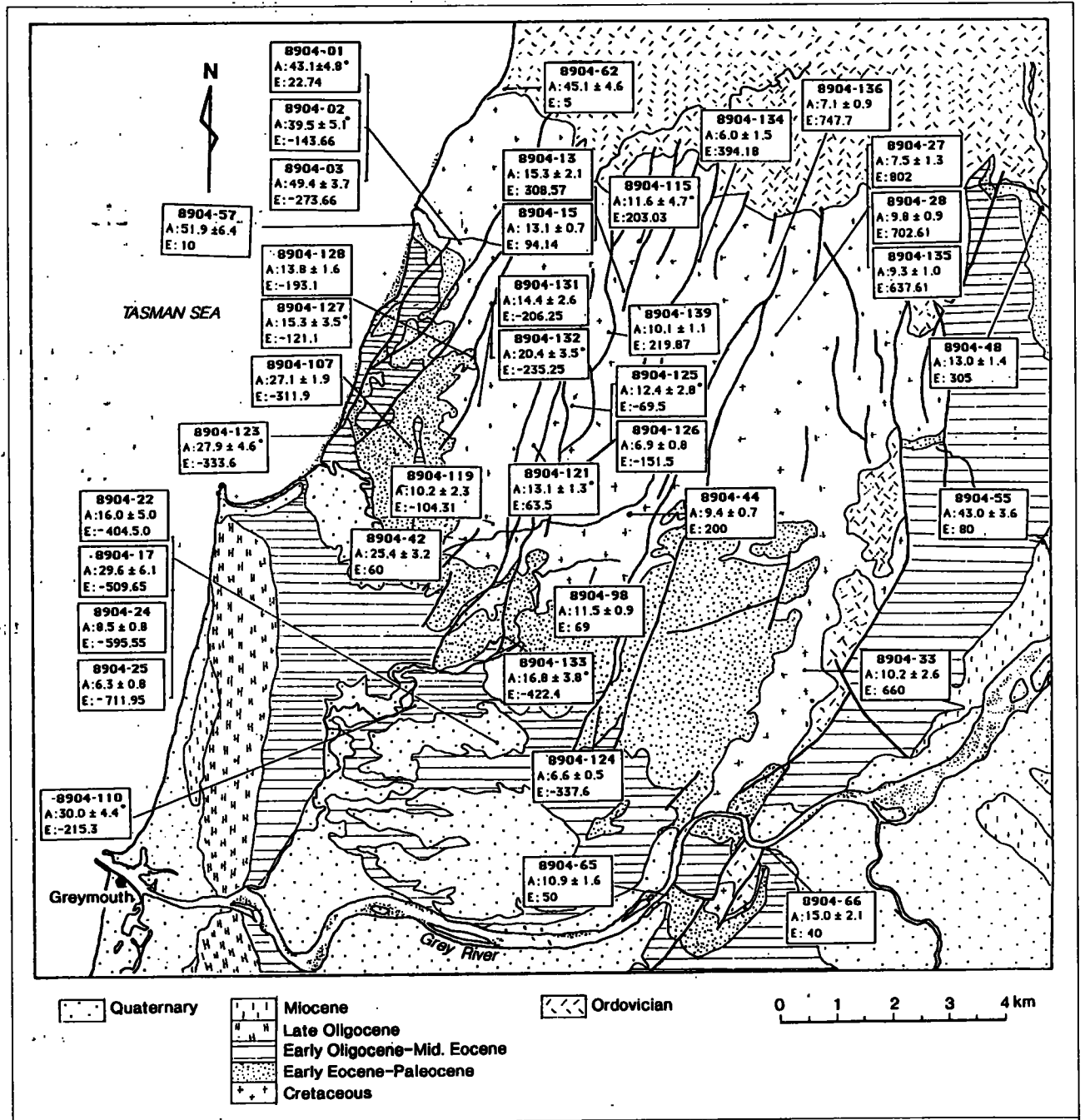


Figure 3: Map of Greymouth Coalfield showing generalised geology and details of sample numbers; location, apatite fission track age and sample elevation with respect to sea level.

The asymmetry of the Brunner-Mt Davy Anticline coincides with major differences between limbs in the thickness of the late Cretaceous-Paleogene succession; the steeper dipping eastern limb has a thinner succession than the shallower dipping western limb (Nathan, 1978)(Figure 3). The structural inversion has clearly exploited the pre-existing geometry of the basin (Paparoa Trough), within which the sedimentary succession accumulated. The thickness variations indicate that in its southern part the Paparoa Trough was a half-graben. Throughout the late Cretaceous-Eocene, and perhaps into the Oligocene, subsidence was controlled by a narrow zone of steeply dipping normal faults (Laird, 1968) located at or near the present location of the Brunner-Mt Davy Anticline, a few kilometres west of the eastern basin margin. Throughout most of this period a structural high existed immediately east of the basin. During the late Eocene it sourced coarse-grained beds that were mass-emplaced into the eastern margin of the basin and across the fault zone (Omotumotu Member, Nathan *et al.*, 1986). Based on extensive map data it seems conclusive that the Neogene inversion of the Paparoa Trough essentially involved a reversal in the sense of movement of pre-existing normal faults, which became reverse faults.

A major asymmetrical syncline, known as the Grey Valley Syncline, occurs immediately east of the Brunner-Mt Davy Anticline (Nathan, 1978), with which it shares a common steeply dipping limb. The axis of the syncline is only 3 to 4 km east of the axis of the anticline. It is a narrow zone considering the amount of section involved, which is accommodated by a combination of rapid eastward thinning of the late Cretaceous-Oligocene beds and unconformity development within the Miocene-Pliocene succession (Figure 2).

These and other stratigraphic-structural features indicate that uplift of the anticlinorium was linked directly to formation and infilling of the Grey Valley Trough, and that uplift must have occurred in stages.

- (i) The youngest beds clearly associated with differential subsidence of the Paparoa Trough are of late Eocene - early Oligocene age (Kaiata Formation). Through the late Oligocene - earliest Miocene (Waitakian Stage) subsidence was more regional, and a thin sequence accumulated over what was to become the Grey Valley Trough; a thicker sequence accumulated over the Paparoa Trough, although this is poorly constrained due to subsequent erosion (Figure 2). The increasing carbonate content upwards through the marine late Eocene-earliest Miocene succession indicates that inversion of the Paparoa Trough and formation of the Grey Valley Trough followed the Waitakian Stage.
- (ii) Within the earliest Miocene (boundary of Waitakian and Otaian stages) there was a sudden influx of terrigenous mudstone, which ended limestone accumulation, and signalled a regionally important tectonic event associated with development of the modern plate boundary (Kamp, 1986). On the western limb of the anticline this mudstone (Inangahua Formation) is structurally conformable with the Oligocene beds and unconformable with the late-early and middle Miocene Stillwater Mudstone, indicating an early phase of inversion during the early Miocene (Otaian - early Altonian stages).

- (iii) The common limb of the anticline and syncline contains steeply dipping marine late-early and middle Miocene mudstone, which in turn is overlain unconformably by marine late Miocene - Pliocene Eight Mile Formation (Figure 2). Further north where the degree of inversion of the Paparoa Trough is greater, the late Miocene beds rest unconformably on the late Eocene-Oligocene beds and basement, or are in fault contact with basement (Nathan, 1978).

In summary, the succession of earliest Miocene to Pliocene marine beds and intervening late-early Miocene and late Miocene unconformities identify at least two phases in the inversion of the Paparoa Trough. A third uplift phase is indicated by the dip and outcrop of the marine Eight Mile Formation. That the Old Man Group, which is conformable with the Eight Mile Formation, is also steeply dipping (45°SE) in the common limb of the anticline and syncline, suggests that the third uplift phase occurred mainly during the Quaternary and led to the present topography. Our fission track data also identify or require these three uplift episodes, and integrated with the stratigraphy of the western limb of the Grey Valley Trough, establish new information about differences in the duration of uplift of the western and eastern limbs of the Brunner - Mt Davy Anticline.

## Apatite Fission Track Analysis

Apatite fission track analysis is based upon measurement under an optical microscope at high magnification (1250 x) of fission track density and track length distributions in apatite grains separated from host rocks. A latent fission track is a linear zone of atomic damage that results from the spontaneous fission of trace amounts of <sup>238</sup>U usually incorporated into apatites at crystallisation. The areal density of spontaneous fission tracks, made visible by acid etching of polished internal grain surfaces, is a function of both uranium content and time; by application of an external mica detector to measure the uranium content (via thermal neutron irradiation) and normalising to geological time using a scale determined by age standards (e.g. Hurford and Green, 1982), fission track ages can be determined for individual grains.

This technique has the potential to reconstruct the variation in paleotemperature in sedimentary basins over the temperature range 20° - 120°C. This arises because the latent tracks in apatite are unstable and anneal (shorten) at temperatures of 20-120°C over time-scales of 10<sup>5</sup> Ma. Consequently, with increasing depth (and temperature) in a stratigraphic succession, the fission track parameters of mean confined track length and sample mean age show a progressive reduction. This is also reflected in track length distributions and single grain age distributions (Green *et al.*, 1989a). Apatites from host rocks that have undergone different thermal histories (i.e. different temperature - time paths) therefore show different density and length parameters. This arises because:

- (i) All tracks have a similar length (~16 μm) when produced (Gleadow *et al.*, 1986).
- (ii) The ultimate length of a track is controlled largely by the maximum temperature that it has experienced (Duddy *et al.*, 1988; Green *et al.*, 1989b).
- (iii) New tracks are progressively added to a sample through time.

Hence the distribution of confined tracks, which controls the age, contains a complete record of the temperature

experienced below about 120°C because each track has experienced a different part of the total thermal history.

Apatite fission track analysis routinely involves the determination of fission track ages for 20 grains of apatite, and also a track length distribution for each sample (normally for 100 tracks). Track length data are derived from horizontally confined tracks, a subset of the total tracks, that lie parallel to the etched surface and totally within the crystal, and have been etched by acid that has passed down an intersecting crack or other track. Such confined tracks provide the most direct measure of the distribution of fission track lengths in an apatite grain, although it is biased against shorter tracks because of their lower probability of intersecting an acid transmitting conduit (Laslett *et al.*, 1982).

The kinetics of fission track annealing for apatite have been established from a series of laboratory experiments (Green *et al.*, 1986; Laslett *et al.*, 1987; Duddy *et al.*, 1988; Green *et al.*, 1989b). Comparisons between the laboratory data and data obtained from simple geological situations have revealed the interplay of temperature and time on the kinetics of annealing. For example, in the laboratory, tracks are totally annealed after 1 hour at a temperature of c.360°C (Green *et al.*, 1986), whereas in a geological setting for timescales of 10–40 Ma, tracks are totally annealed at c.125°C (Gleadow *et al.*, 1983). Superimposed upon the controls of temperature and time on annealing is apatite composition, specifically the Cl/(F + Cl) ratio (Green *et al.*, 1986); in a sample containing a range of apatite compositions, those grains richest in fluorapatite will anneal at a slightly faster rate than more chlorapatite rich grains. At temperatures of 90°–100°C, and time scales of 10 Ma or more, these differences will be maximised, as shown by distributions of single grain ages and track lengths (Green *et al.*, 1989b) and, in sequence with other samples, can be very diagnostic of the temperatures attained by the rocks.

## Sample Details

In this study we processed 136 samples obtained from basement and the overlying sedimentary succession from different parts of both limbs of the Brunner-Mt Davy Anticline, of which 40 samples yielded sufficient apatites for analysis (Whitehouse, 1991). Details of sample location, elevation and stratigraphic position and age are given in Table 1. Many of the samples were obtained from cores drilled as part of the Coal Resources Survey and curated in Christchurch. One to 1.5 kg of sandstone sampled from cores was processed, and generally 2 kg of outcrop sample was processed. Samples with reasonable yields of apatite came chiefly from the Rewanui Member and the Island Sandstone.

## Experimental Procedures

Apatite concentrates were separated from the samples using standard magnetic and heavy liquid techniques. Apatite grains were mounted in Araldite<sup>(R)</sup> on microscope slides, ground using 400 and 600 grade silicon carbide papers, and polished using 'A' alumina. The apatites were then etched in 5M HNO<sub>3</sub> for 20 sec at room temperature. The mounts were cleaned and sealed in intimate contact with low-U muscovite external detectors using heat shrink plastic film, stacked in an aluminium can between two pieces of uranium dosimeter glass (SRM612), and irradiated in the X-7 facility of the HIFAR reactor, Lucas Heights, N.S.W. A nominal

influence of approximately  $1 \times 10^{16}$  thermal neutrons cm<sup>-2</sup> was used for each irradiation.

After irradiation the muscovite external detectors were detached and etched in 40% HF for 20 min at room temperature. The counting of track densities was carried out using a Zeiss<sup>(R)</sup> Universal microscope, with a true overall linear magnification of 1068 x using dry objectives. The external detector method (see Gleadow, 1981) has been used throughout this study, using an Autoscan<sup>TM</sup> microcomputer controlled automatic stage. The fission track ages reported here were determined using the zeta calibration method (Hurford and Green, 1982; Green, 1985).

Confined track lengths in apatite sample mounts were measured using a microcomputer-linked HIPAD<sup>TM</sup> digitising tablet superimposed on the microscope field of view via a projection tube. With this system, calibrated against a stage graticule ruled in 2 µm divisions, individual tracks can be measured with a precision of ± 0.2 µm. Tracks were measured only in prismatic grains, characterised by sharp polishing scratches with well etched tracks of narrow cone angle in all orientations, because of the anisotropy of annealing of fission tracks in apatite (as discussed by Green *et al.*, 1986). Tracks were also measured following the recommendations of Laslett *et al.* (1982), the most important of which is that only horizontal tracks should be measured. One hundred tracks were measured whenever possible. In apatite samples with low track density, fewer confined tracks may be available, and in such cases, the whole mount was scanned to measure as many confined tracks as possible.

## Data Analysis

Analytical data are shown in Table 2. Fission track ages were calculated using the standard fission track age equation (Hurford and Green, 1982) with conventional errors (Green 1981), calculated from the total number of tracks counted and reflecting purely Poissonian variation, quoted at ± 1σ. In some samples a significant spread in single grain ages can result from either inheritance of detrital grains from mixed source areas, or differential annealing in grains of different composition by heating above about 90°C (Green *et al.*, 1989a). In these samples the conventional method of age estimation (Green, 1981) is not valid, being biased towards grains with higher track counts. These samples can be detected by a Chi squared statistic (Galbraith, 1981) that indicates the probability of grains counted in a sample belonging to a single population of ages. A probability of less than 5% is taken as evidence that the grains represent a mixed age population with real differences between the fission track ages of individual grains, due to compositional differences or mixed provenance. Where a significant spread of ages is present within a sample ( $P(x^2) < 5\%$ ) the mean age provides a useful measure (Green 1981, Green *et al.* 1989a) and this parameter is quoted in Table 2 where appropriate. The error in the mean age is taken as the standard deviation of the individual grain ages.

## Results and Interpretations

Apatite fission track age and length data for samples from the field area are given in Table 2. The age together with the elevation of each sample site with respect to sea level are shown on a simplified geological map of the field area (Figure 3). The systematic changes in the fission track data across the coalfield are best illustrated in a series of cross-

Sample	Map Reference	Drillhole Reference	Sample Elevation, m	Formation Member	Stratigraphic Age (Stage)
8904-01	J31 675726	DH621	22.7	Rewanui	late Cret.
8904-02	J31 675726	DH621	-143.7	Rewanui	late Cret.
8904-03	J31 675726	DH621	-273.7	Rewanui	late Cret.
8904-13	K31 705719	DH656	308.6	Rewanui	late Cret.
8904-15	K31 705719	DH656	94.1	Morgan	late Cret.
8904-17	J31 684642	DH654	-509.7	Morgan	late Cret.
8904-22	J31 684642	DH654	-404.5	Goldlight	late Cret.
8904-24	J31 684642	DH654	-595.6	Rewanui	late Cret.
8904-25	J31 684642	DH654	-711.95	Rewanui	late Cret.
8904-27	K31 735714	DH659	802.0	Rewanui	late Cret.
8904-28	K31 735714	DH659	702.6	Rewanui	late Cret.
8904-33	K31 740647	outcrop	660.0	Dunollie	late Cret.
8904-42	J31 676613	outcrop	60.0	Dunollie	late Cret.
8904-44	K31 706678	outcrop	200.0	Rewanui	late Cret.
8904-48	K31 780733	outcrop	305.0	basement	Ordovician
8904-55	K31 781675	outcrop	80.0	Eight Mile	(Tk-Wo)
8904-57	J31 667729	outcrop	10.0	Island Sst	(Kaiatan)
8904-62	J31 676749	outcrop	5.0	basement	Ordovician
8904-65	K32 715610	outcrop	50.0	Island Sst	(Kaiatan)
8904-66	K32 734618	outcrop	40.0	Island Sst	(Kaiatan)
8904-98	K31 708675	DH630	69.0	Rewanui	late Cret.
8904-107	J31 667689	DH642	-311.9	Rewanui	late Cret.
8904-110	J31 667644	DH655	-215.3	Island Sst	(Kaiatan)
8904-115	K31 707723	DH663	203.0	Rewanui	late Cret.
8904-119	J31 683676	DH623	-104.3	Rewanui	late Cret.
8904-121	J31 687688	DH624	63.5	Rewanui	late Cret.
8904-123	J31 565692	DH626	-333.6	Rewanui	late Cret.
8904-124	K31 707644	DH627	-337.6	Rewanui	late Cret.
8904-125	J31 693695	DH632	-69.5	Rewanui	late Cret.
8904-126	J31 693695	DH632	-151.5	Rewanui	late Cret.
8904-127	J31 678710	DH635	-121.1	Rewanui	late Cret.
8904-128	J31 678710	DH635	-193.1	Rewanui	late Cret.
8904-131	J31 674702	DH645	-206.3	Rewanui	late Cret.
8904-132	J31 674702	DH645	-235.3	Rewanui	late Cret.
8904-133	J31 687662	DH651	-422.4	Rewanui	late Cret.
8904-134	K31 727726	DH658	394.2	Rewanui	late Cret.
8904-135	K31 735714	DH659	637.6	Rewanui	late Cret.
8904-136	K31 734722	DH660	747.7	Rewanui	late Cret.
8904-139	K31 707713	DH666	219.9	Rewanui	late Cret.

Sample elevation expressed in relation to sea level. Tk is abbreviation for Tongaporutuan stage, and Wo for Opoitian stage.

Table 1: Details of Greymouth Coalfield samples analysed.

sections, one each for the northern, central and southern parts of the coalfield, in which sample mean age and mean length are plotted with respect to distance from the Mt Davy fault zone.

#### Northern Region

In Figure 4 the apatite fission track ages reduce from about 50 Ma for samples near the coast to a minimum of 6 Ma some 4 to 5 km west of the fault zone. One sample (8904-48) further east has a higher age value of  $13.0 \pm 1.4$  Ma. In each sample in this transect the fission track age exceeds the

stratigraphic age of the unit sampled, indicating that all samples have been subjected to higher paleotemperatures in the past. The form of the age profile is very similar to the pattern typically obtained down a well section that has undergone inversion (cooling): the interval of pronounced age reduction corresponds to an exhumed annealing zone (10 to 7 km from the fault zone) and the plateau interval corresponds to rocks buried (heated) to temperatures above the resetting temperature of fission tracks in apatite.

Consideration of the track length data together with the age data demonstrate clearly that we are dealing with some

samples that formerly resided within an annealing zone at elevated temperatures, and other samples that passed through an annealing zone after uplift commenced. On the mean length versus age plot (Figure 4) the samples that resided within the annealing zone are identified by their older age and shorter lengths. Within this zone note that samples sequentially closer to the Mt Davy fault zone (Figure 4) have correspondingly shorter mean track lengths. This is consistent with the more easterly samples having resided formerly at deeper levels in the exhumed annealing zone. The samples from the reset zone have noticeably longer mean lengths than the samples from the annealed zone. In summary, the general pattern of the fission track data in the northern transect indicates that sediments now at or near the surface were heated to progressively higher temperatures eastward across the coalfield to the fault zone; a corollary of this is that the degree of subsequent inversion also increased eastward to the fault zone.

Within the zone of reset samples there are two discrete groupings that indicate details about the uplift history. Samples originating a few kilometres west of the fault zone have younger ages and longer mean lengths than samples originating further west from the fault zone, which have older ages and longer mean lengths (Figure 4). These groups

probably result from two separate uplift phases. The first uplift phase would have involved inversion of the whole basin. It caused initial cooling of the annealing zone now fossilised in the western part of the coalfield, but the direct evidence is only recorded in a narrow zone 1 to 2 km wide immediately east of the base of the exhumed annealing zone (samples 8904-13, 15 and 115). These samples had earlier been heated via burial to temperatures just above the base of the annealing zone, and would therefore be the first rocks to record cooling as a consequence of uplift. That only a narrow zone of the coalfield records the first phase of cooling suggests that the uplift was probably limited to a few hundred metres in that part of the coalfield. While this amount of uplift was sufficient to cool these rocks below the closure temperature, they resided nevertheless at elevated temperatures within an annealing zone until they were cooled further by the second uplift phase. The second group of samples (8904-27, 28, 134, 135 and 136) would have been uplifted during the first phase, but at that time did not cool sufficiently to enter the annealing zone and hence retain a record of uplift; this would have happened during the second uplift phase. Sample 8904-48 from east of the Mt Davy fault zone groups with the reset samples furthest west from the

Sample	Number of Grains	Spontaneous		Induced		P(X <sup>2</sup> ) (%)	ps/pi ± 1σ	Dosimeter		Age ± 1σ, Ma	Mean Track Lengths	
		ps	(Ns)	pi	(Ni)			pd	(Nd)		mean ± 1σ, μm	(N)
8904-01	23	0.483	467	2.003	1937	0.01	0.283 ± 0.031	0.874	8293	43.1 ± 4.8	10.42 ± 0.28	86
8904-02	25	0.491	297	2.344	1419	0.01	0.259 ± 0.033	0.874	8293	39.4 ± 5.1	10.10 ± 0.70	18
8904-03	22	0.499	247	1.536	760	12.5		0.874	8293	49.4 ± 3.7	8.76	1
8904-13	25	0.126	62	1.254	616	87.3		0.874	8293	15.3 ± 2.1	12.51 ± 1.07	3
8904-15	19	0.248	385	2.899	4494	10.1		0.874	8293	13.1 ± 0.7	12.48 ± 0.30	48
8904-17	20	0.061	28	0.312	144	98.9		0.874	8293	29.6 ± 6.1	13.94	1
8904-22	9	0.161	48	2.224	662	1.5	0.105 ± 0.033	0.874	8293	16.0 ± 5.0	11.46 ± 1.52	3
8904-24	8	0.237	124	4.611	2407	5.3	0.044 ± 0.007	0.944	4472	7.3 ± 1.2		
8904-25	16	0.109	69	2.821	1781	48.4		0.938	4448	6.3 ± 0.8	9.90 ± 1.33	5
8904-27	9	0.178	34	3.890	740	15.6		0.933	4423	7.5 ± 1.3	13.57 ± 0.40	3
8904-28	19	0.167	136	2.771	2249	65.9		0.927	4398	9.8 ± 0.9	13.10 ± 0.32	24
8904-33	8	0.005	16	0.727	252	100		0.923	4374	10.2 ± 2.6		
8904-42	6	0.539	76	3.356	473	77.8		0.907	4267	25.4 ± 3.2	9.69 ± 0.77	9
8904-44	17	0.248	195	4.168	3277	9.6		0.902	4275	9.4 ± 0.7	12.56 ± 0.30	31
8904-48	20	0.172	91	2.065	1091	11.7		0.896	4250	13.0 ± 1.4	11.76 ± 0.50	11
8904-55	20	0.463	194	1.668	699	14.2		0.892	4226	43.0 ± 3.6	12.99 ± 0.20	24
8904-57	20	0.649	153	2.291	540	2.6	0.337 ± 0.041	0.886	4201	51.9 ± 6.4	12.24 ± 0.20	19
8904-62	20	0.891	129	3.026	438	94.1		0.881	4176	45.1 ± 4.6	11.10 ± 0.50	11
8904-65	18	0.143	50	2.010	700	77.0		0.876	4151	10.9 ± 1.6	8.43 ± 1.93	3
8904-66	18	0.150	56	1.526	568	97.3		0.871	4127	15.0 ± 2.1	11.80 ± 0.73	13
8904-98	19	0.265	185	3.489	2432	19.7		0.865	4102	11.0 ± 0.9	10.36 ± 0.40	36
8904-107	20	0.561	265	3.103	1465	79.8		0.863	4078	27.1 ± 1.9	8.60 ± 0.68	12
8904-110	13	0.574	114	4.339	861	0.01	0.201 ± 0.029	0.855	4053	30.0 ± 4.4	12.09 ± 0.72	2
8904-115	20	0.106	34	1.782	571	0.01	0.092 ± 0.038	0.719	3408	11.6 ± 4.7	13.31 ± 1.07	6
8904-119	9	0.132	21	1.652	262	26.2		0.732	3470	13.2 ± 6.7		
8904-121	20	0.218	247	2.279	2578	3.0	0.102 ± 0.010	0.739	3501	13.1 ± 1.4	10.13 ± 0.50	19
8904-123	20	0.258	145	1.297	727	0.01	0.215 ± 0.035	0.745	3532	27.9 ± 4.6	10.89 ± 0.49	8
8904-124	20	0.157	161	3.140	3219	73		0.752	3562	6.6 ± 0.5	12.01 ± 0.30	16
8904-125	20	0.232	251	2.763	2983	0.01	0.094 ± 0.021	0.758	3592	12.4 ± 2.8	13.02 ± 0.86	5
8904-126	20	0.099	80	1.904	1528	89.3		0.764	3624	7.0 ± 0.8	11.33 ± 0.54	4
8904-127	22	0.102	66	1.275	822	0.3	0.114 ± 0.026	0.771	3655	15.3 ± 3.5		
8904-128	20	0.164	85	1.609	833	50.1		0.776	3686	13.8 ± 1.6	14.59	1
8904-131	19	0.129	35	1.228	333	95.7		0.784	3717	14.4 ± 2.6	9.11 ± 0.94	3
8904-132	19	0.140	40	0.946	269	44.7		0.790	3747	20.4 ± 3.5	10.51 ± 0.83	8
8904-133	20	0.174	88	2.738	1381	0.01	0.121 ± 0.027	0.800	3778	16.8 ± 3.8	9.88 ± 0.64	2
8904-134	12	0.057	17	1.346	398	73.5		0.804	3809	6.0 ± 1.5	12.43	1
8904-135	16	0.199	106	3.031	1609	54.5		0.810	3839	9.3 ± 1.0	13.32 ± 0.53	8
8904-136	20	0.138	67	2.784	1348	39.1		0.817	3870	7.1 ± 0.9	12.94 ± 0.64	5
8904-139	20	0.276	209	3.736	2831	0.4	0.070 ± 0.008	0.823	3901	10.1 ± 1.2	12.26 ± 0.60	21

Track densities (P) are as measured and are (10<sup>6</sup> tracks cm<sup>-2</sup>); number of tracks counted shown under (N). Apatite analyses made by external detector method using 0.5 for the 4π/2π geometry correlation factor. Apatite age was calculated using dosimeter glass SRM 612, and calculated with a zeta-612 = 348.7 ± 4.8 (analyst I.W.S.W). P(X<sup>2</sup>) is probability of obtaining X<sup>2</sup> value for v-degrees of freedom (where v = number of crystals - 1); mean Ps/Pi ratio used to calculate age and uncertainty where P(X<sup>2</sup>) < 5%.

Table 2: Apatite fission track results, Greymouth Coalfield

fault zone, and indicates that parts of the eastern limb of the anticline also cooled during the first uplift phase.

The ages of the uplift phases cannot be taken directly from the measured age of the reset samples, as some track density and hence age has been lost due to shortening of tracks as they passed up through the annealing zone: their mean lengths of 12-14  $\mu\text{m}$  are less than the etchable birth length of about 16  $\mu\text{m}$ . Using a length-density relationship (Green, 1988), we can correct the ages for this track length reduction. In the northern transect, the group of reset samples furthest from the fault zone started to retain tracks as a result of uplift from about 16 Ma, and the samples closer to the fault zone were uplifted from about 9 Ma.

### Central Region

The patterns in the fission track data in the central region of the coalfield are similar to those in the northern transect, and are interpreted in a similar fashion. Based on the mean length-age relationship of the samples (Figure 5), the base of the exhumed annealing zone is placed at 8 km west of the Mt Davy fault zone, all of the samples to the east having been heated sufficiently to reset the track density. On the mean length-age plot two groups emerge within the reset samples, one indicating uplift started at about 20 Ma, and the other indicating uplift started at about 11 Ma.

### Southern Region

The fission track data for the southern part of the coalfield also identify a western exhumed annealing zone and an eastern zone of reset ages, which involves both the western and eastern limbs of the Brunner-Mt Davy Anticline (Figure 6). As with the other transects, there are two groups within the reset samples, one that started to accumulate tracks from about 18 Ma, and another that started to accumulate tracks from about 8 Ma. In this transect the group of samples with younger ages have shorter mean track length values than samples with young ages further north in the coalfield. This is considered to be a manifestation of the plunging anticline structure. Here the host rocks have much lower elevations than equivalent stratigraphic units sampled further north in the coalfield, and therefore they have cooled more slowly through the modern annealing zone, which has resulted in a greater degree of annealings.

### Apatite Composition

Apatite composition, specifically chlorine content, is known to have a control on the annealing properties of latent fission

tracks. Green *et al.* (1988) demonstrated for a sample taken from 92°C in Flaxman's-1 well (Otway Basin) that chlorine content is positively correlated with degree of annealing: grains with <0.05 chlorine atoms per molecule have essentially no track density, whereas grains with 0.5 chlorine atoms per molecule are unaffected by annealing at temperatures up to 92°C and retain their depositional age. Chlorapatite crystals are therefore more retentive of tracks than fluorapatites, and we essentially have a fine spectrum of thermochronometers within the one (fission track) system. An effect of the compositional control on annealing is that the temperature of the base of the annealing zone will vary depending on the particular composition of the apatites being analysed from a field area.

To constrain the temperature at which the apatites were reset in the Greymouth Coalfield we determined by microprobe analysis the chlorine contents of apatites in seven samples from different stratigraphic units and parts of the coalfield. The results are given in Table 3. The detectable limit of the JOEL superprobe (Analytical Facility, Victoria University of Wellington) for chlorine is ~0.05 wt percent. Only 23% of the grains across all samples have a chlorine content greater than 0.1 percent, and all but 10% of these grains occur in one sample (8904-110). Excluding sample 8904-110, the sample mean values range from 0.026 to 0.353 wt % chlorine (Table 3). The majority of the apatites are therefore fluorapatites consistent with the granitic source of the Rewanui Member. Durango apatite, the standard apatite upon which most of the laboratory experiments have been undertaken to better understand the kinetics of annealing (Green *et al.*, 1986), has an average chlorine content of about 0.43 wt percent. The temperature of total annealing of fission tracks in Durango apatite under geological conditions where time is not a limiting factor is usually taken to be about 110°C. Otway basin apatites, which have chlorine values ranging up to 0.6 wt %, are fully annealed at 125°C (Green *et al.* 1985). In the absence of a detailed data base of the temperatures of complete annealing of fission tracks in apatites of the whole spectrum of compositions, and given the fluorapatite composition of the majority of the apatites analysed from the Greymouth Coalfield, it is reasonable to assume that the sediments at the base of the exhumed annealing zone in the coalfield experienced a peak temperature of about 100°C.

The particular grains microprobed for chlorine composition were also the grains analysed for track density (age). This allows age to be plotted against wt % chlorine for

Sample	Mean Wt% Chlorine	Range (Wt% Cl)	Number of Crystals	Stratigraphic Unit
8904-27	0.066	0.004 - 0.353	9	Rewanui
8904-42	0.026	0.000 - 0.060	6	Rewanui
8904-44	0.057	0.002 - 0.155	15	Rewanui
8904-110	0.308	0.009 - 0.630	12	Island Sst
8904-123	0.043	0.001 - 0.246	8	Rewanui
8904-131	0.028	0.001 - 0.144	14	Rewanui
8904-139	0.042	0.007 - 0.120	18	Rewanui

Table 3: Composition of apatite, Greymouth Coalfield.

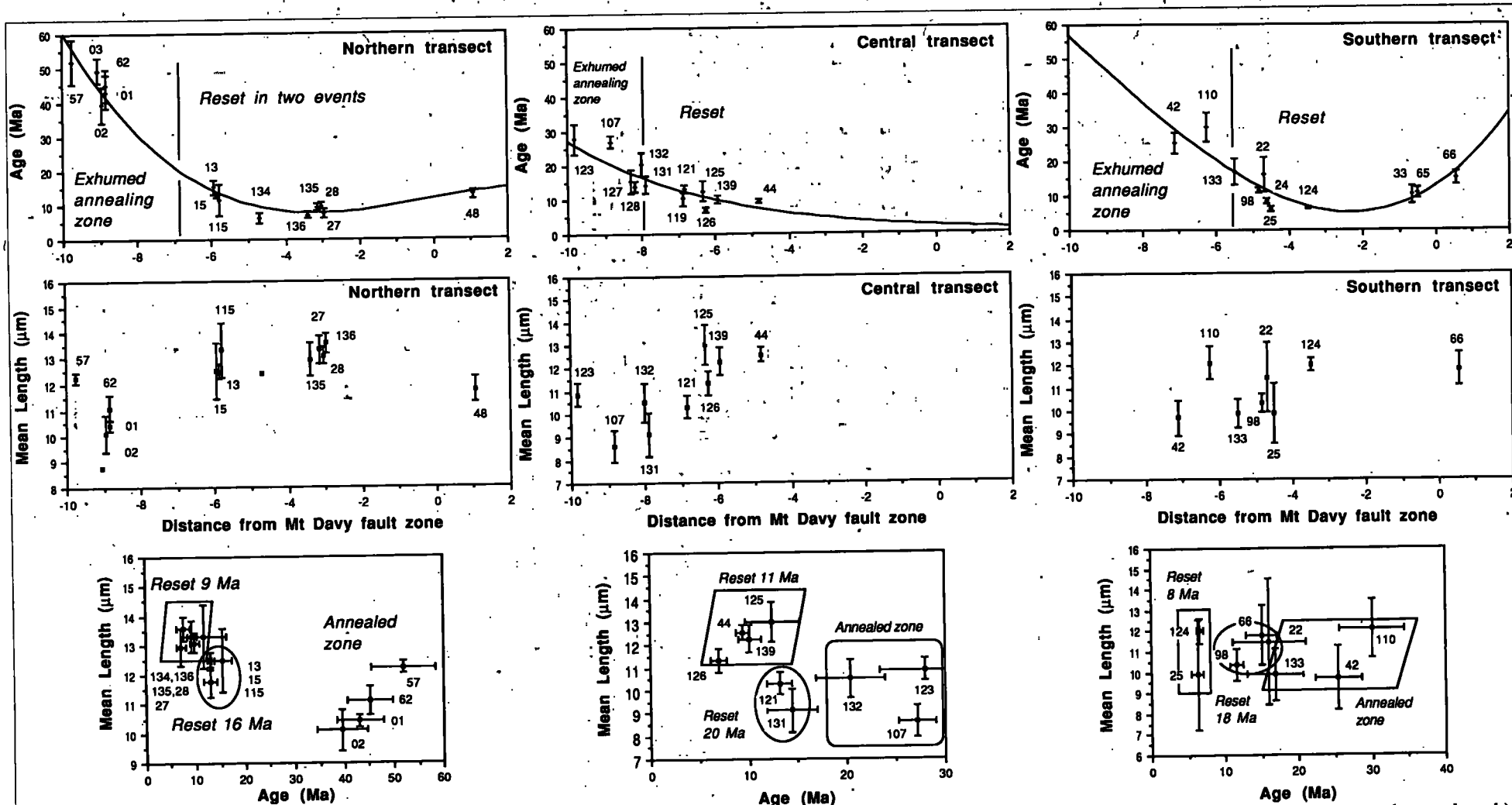


Figure 4: Fission track data (mean age and mean length) for the northern region of the Greymouth Coalfield, expressed in upper two diagrams with respect to distance orthogonal from the Mt Davy fault zone. Transects oriented west to east.

Figure 5: Fission track data (mean age and mean length) for the central region of the Greymouth Coalfield, expressed in upper two diagrams with respect to distance orthogonal from the Mt Davy fault zone. Transects oriented west to east.

Figure 6: Fission track data (mean age and mean length) for the southern region of the Greymouth Coalfield, expressed in upper two diagrams with respect to distance orthogonal from the Mt Davy fault zone. Transects oriented west to east.

each grain in the samples analysed (Figure 7). In the four samples from the reset zone (8904-27, 44, 131 and 139) there is a slight trend for age to be positively correlated with chlorine content, but generally the range of chlorine contents is very low, often strictly below the detectability limit of the microprobe. All but sample 8904-139 passed the Chi squared test. In the samples from the exhumed annealing zone (8904-42 and 110) age is positively correlated with chlorine content, strongly in the case of 8904-110, but this is opposite to that in sample 8904-123, which has one outstanding grain with higher chlorine content (0.246 wt %) but little age (Figure 7). As noted earlier, 8904-110 is the only sample with apatites showing a large range of chlorine contents. All the other samples derived from Rewanui Member, whereas 8904-110 comes from late Eocene Island Sandstone, which was probably sourced from a greater range of basement types than for the Rewanui Member. Samples 8904-42 and 110 were heated to lower levels of the exhumed annealing zone (Figure 6), probably to temperatures of 90°C or higher. This would have allowed the more fluorine-rich apatites in these samples to become more heavily annealed than the chlorine-rich grains. Sample 8904-110 failed the Chi squared test, but 8904-42 passed, perhaps reflecting the greater uncertainty associated with its single grain ages.

#### **Paleotemperature Distribution**

Based on the fission track results and interpretations made so far, the coalfield can be subdivided into three zones (Figure 8).

- (i) An exhumed annealing zone in the west in which the late Cretaceous-late Eocene section experienced temperatures up to 100°C.
- (ii) A narrow zone to the east where the same stratigraphic units were heated by burial to temperatures exceeding 100°C, but cooled below 100°C between 19.5 and 15.5 m.y. ago. This zone wraps around the nose of the Brunner - Mt Davy Anticline in the vicinity of the Grey River, and continues north-northeastward parallel to the fault zone (Figure 8). At present this part of the zone is constrained by few samples, chiefly because most of those processed from this part of the coalfield contained no apatites due to diagenetic replacement by pyrite.
- (iii) The central part of the coalfield lies within a zone where the late Cretaceous section was heated much higher than 100°C, cooled to some extent in the early Miocene, and cooled below 100°C between 12 and 8 m.y. ago. The rocks lying along the boundary marked "Base Phase 1 annealing zone" in Figure 8 would have resided at about 100°C between the first and second uplift phases; the peak temperatures experienced were however higher than 100°C and were achieved just before the first uplift phase started.

The boundaries between the three zones mapped in Figure 8 apply to rocks at or near the surface. The boundaries do of course dip, and the direction of dip is shown on them in Figure 8, which is consistent with the plunging anticlinal structure of the coalfield.

The fission track results were a surprise to us to the extent that the base of the exhumed annealing zone was further west in the coalfield than we had anticipated. This has limited the extent of the coalfield over which detailed estimates of the maximum paleotemperatures can be made; this is only

possible in (fossil) annealing zones where the fission track parameters of length and density express temperature differences in the range 50 to 100-125°C. However, the extent of the reset zone, where it is only possible to put minimum limits (100°C) on the temperatures experienced, gives very good constraints on the timing of inversion, as we explore below.

In Figure 8 we have contoured the observed fission track ages within the exhumed annealing zone at 10 m.y. intervals. Because the ages are all much less than the stratigraphic ages, and the apatites are essentially monocompositional, the ages will manifest the distribution of paleotemperatures in the rocks. Careful assessment of the fission track data, especially the length distributions, indicates that the 90°C isotherm approximates the 30 m.y. isoage line, and the 80°C isotherm approximates the 50 m.y. isoage line. This paleotemperature distribution can be compared with vitrinite reflectance values ( $R_o$  max, %) for the Rapahoe sector of the coalfield (Figure 9), as interpreted by Newman (1987). Not surprisingly, the paleotemperature and vitrinite reflectance patterns are similar to one another, reflecting their common origin due to depth of burial. A lack of fission track data at the seaward end of Seven Mile Creek precludes identification of the details evident in the vitrinite reflectance map.

#### **Paleotemperature Maxima in Rapahoe Sector compared with Vitrinite Reflectance**

An objective at the outset of this study was to relate coal rank to paleotemperature. Because the base of the exhumed annealing zone is so far west, the opportunity to do this is limited, but it is possible in the Rapahoe sector. Figure 10 compares for the Rapahoe sector maximum paleotemperature assessed from the fission track data with vitrinite reflectance. Vitrinite reflectance values appear to linearly increase from 0.5 to 0.67% over the temperature range 82 to 100°C.

#### **Timing of Inversion and its Relationship to the Formation of the Grey Valley Syncline**

The fission track data identify directly two uplift phases within the reset zone of the coalfield. Using the length-density relationship of Green (1988), we have combined the errors associated with the observed sample ages and the errors surrounding the sample mean lengths to construct a probability distribution of the corrected apatite fission track ages (Figure 11). The graph shows the two uplift phases, one extending from 19.5 to 15.5 Ma, and the other from 12 to 7 Ma. The way to read the graph is that there is a high probability (5 and higher on x scale) of uplift occurring during the limits just given, but uplift outside these limits cannot be excluded statistically. We think that in each phase uplift genuinely extended over a time range, but not the full statistical range. For example, uplift from 25 to 22 Ma is not consistent with the accumulation of Cobden Limestone in the Paparoa Trough.

Each of the two uplift phases that inverted the Paparoa Trough and formed the anticlinorium over the coalfield coincide with unconformities within the Miocene-Pliocene stratigraphic section of the limb of the Grey Valley Syncline in common with the anticline. (Figure 2). The ~19.5 Ma start of the first phase of uplift of the Brunner-Mt Davy Anticline sits neatly within the unconformity between the

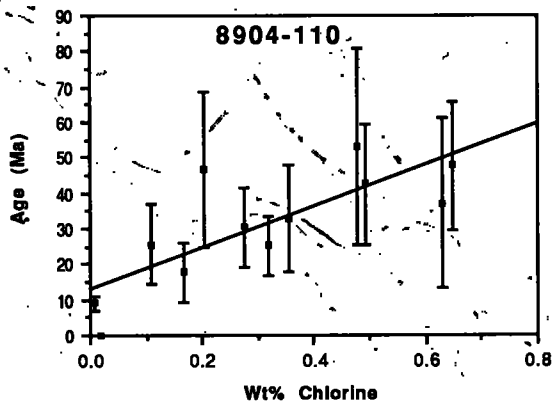
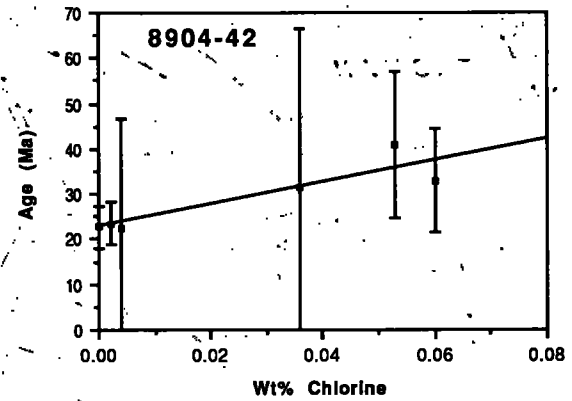
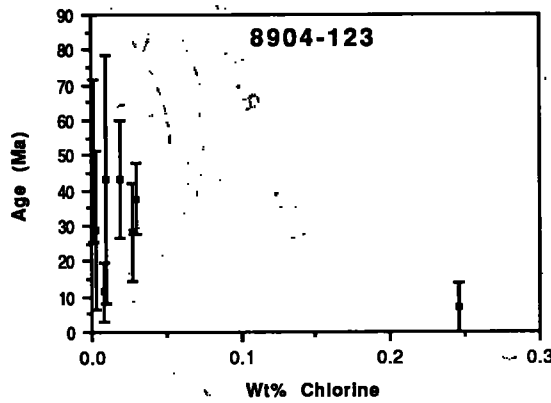
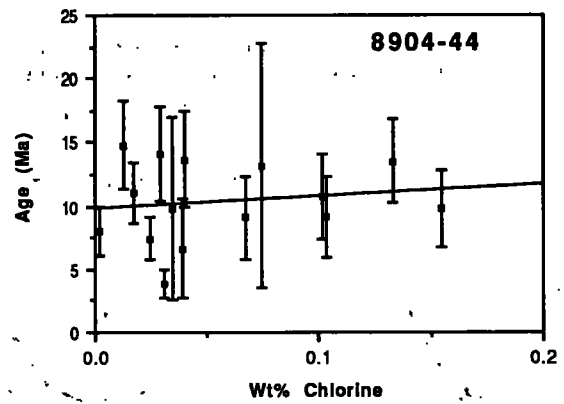
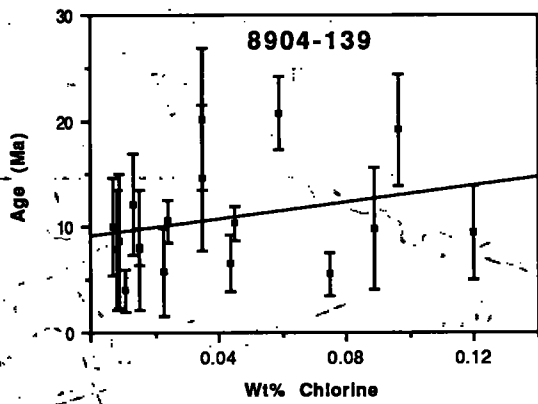
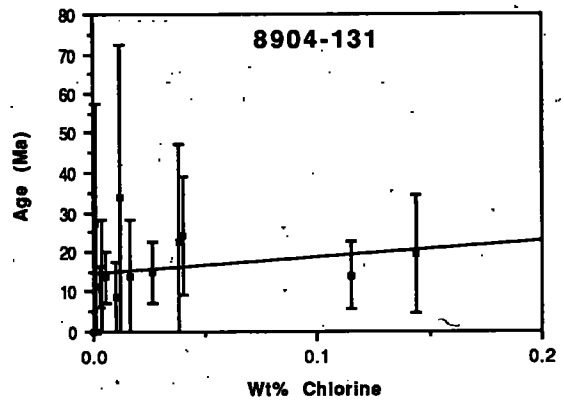
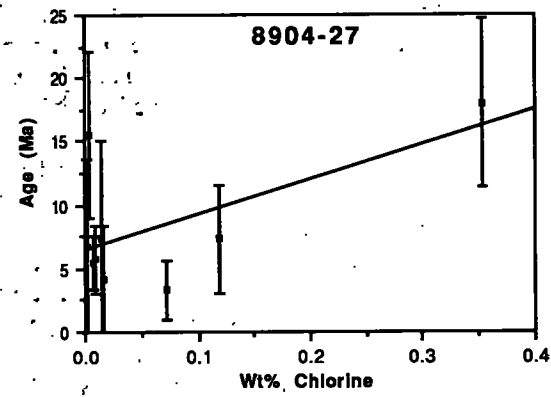


Figure 7: Individual grain fission track age versus Wt% chlorine content for apatites within seven different samples. Sample 8904-27 is from northern region, samples 8904-131, 139, 44, and 123 are from the central region, and samples 8904-42 and 110 are from the southern region of the coalfield.

limestone and Stillwater Mudstone. This uplift phase probably continued until about 15.5 Ma, which is 1 to 2 million years after accumulation of Stillwater Mudstone started (Altonian Stage) in the western limb of the syncline, which is also the eastern limb of the anticline. The time span of uplift, the occurrence of an early Miocene unconformity and the occurrence of late-early Miocene marine sedimentation on the western limb of the syncline can all be reconciled in the following way. When the study area became compressive, both sides of the normal fault zone within the Paparoa Trough became coupled and consequently both sides of the fault were uplifted, causing erosion that contributed to unconformity development along the eastern margin. With continued early Miocene compression, the fault zone became decoupled; the effect of reverse faulting and uplift of the western limb of the anticline was to load the eastern limb, which subsided and accumulated Stillwater Mudstone.

This sequence of structural events was repeated during the late Miocene. The second phase of uplift from 12 to 7 Ma, recorded by fission tracks west of the Mt Davy fault zone, coincides with a late Miocene unconformity between

Stillwater Mudstone and Eight Mile Formation (Figure 11). In places the Rotokohu Coal Measures, a regressive sequence, intervenes between the two mudstone formations (Nathan, 1978). Differences in dip of the beds either side of the late Miocene unconformity again indicate an initial period of coupling across the fault zone resulting in uplift of both the western and eastern limbs of the anticline, and subsequent continued uplift of the western limb of the anticline and subsidence of the eastern limb (western limb of Grey Valley Syncline). The fission track timing of inversion together with the structural-stratigraphic relationships show clearly that the inversion of the Paparoa Trough was episodic and that inversion of this trough was linked directly to downwarping of the adjacent Grey Valley Trough. This type of development is similar to that observed elsewhere along the inner margins of foreland basins.

Whether the late Miocene phase of uplift genuinely ended at about 7 Ma or whether this is an artifact of the limitation of our sampling to rocks on or near the surface is difficult to establish. The late Miocene uplift phase may have continued through to the present, or alternatively, the present topography may have originated during a third and

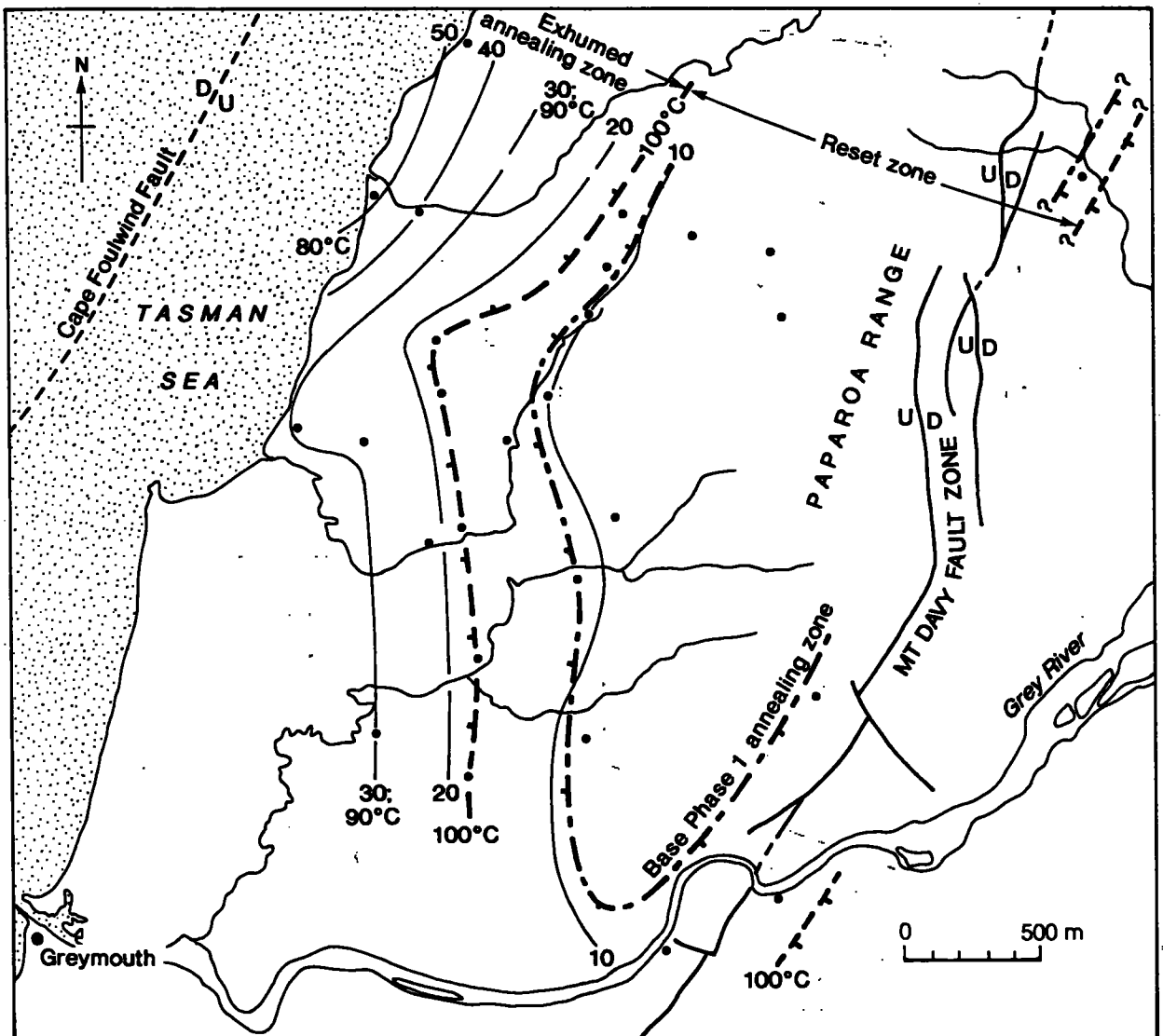


Figure 8: Map showing 10, 20, 30, 40, and 50 apatite fission track isoage lines in the western part of the Greymouth Coalfield, 80°, 90° and 100°C paleoisotherm lines, and the extent of the exhumed annealing zone and reset zone over the coalfield. Sample locations shown as dots.

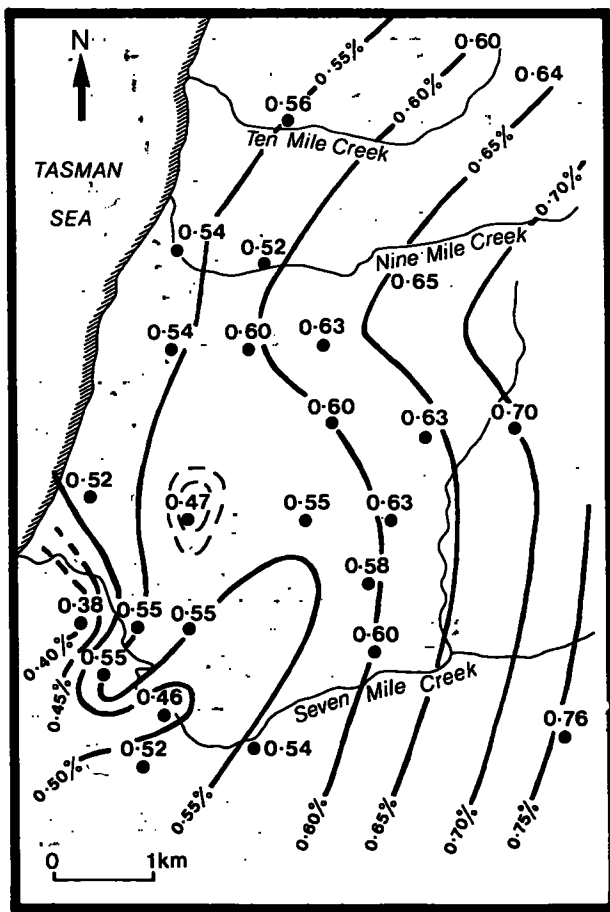


Figure 9: Distribution of Vitrinite Reflectance ( $R_o$  max %) values over the Rapahoe Sector of the Coalfield (From Newman, 1987).

separate uplift phase. The Pliocene-Pleistocene stratigraphy of the Grey Valley Trough has previously been interpreted to suggest that most of the present basin-and-range topography originated during the Quaternary (Nathan *et al.*, 1986). Certainly substantial post-Pliocene uplift is required from the dip ( $45-60^\circ$ ) of the Eight Mile Formation and overlying early Pleistocene Old Man Group in the western limb of the Grey Valley Syncline. It can also be argued that in order to see the fission track evidence of the two earlier phases of uplift, there must have been a subsequent and major uplift phase to bring to the surface rocks that contain apatites in which the fission tracks were reset 3 to 4 km down at  $100^\circ$  Celsius. We favour there having been a third (Quaternary) uplift phase that contributed to inversion of the Paparoa Trough and folding of the Grey Valley Syncline.

### Timing of Inversion in Relation to Regional Tectonics

The two uplift phases relate closely to the wider development of the modern Australia-Pacific plate boundary, which broke through New Zealand in the late Oligocene (28-24 Ma) (Kamp 1986, 1991). The start of inversion of the southern Paparoa Trough was evidently delayed by a few million years, probably because it is located some distance from the plate boundary (Alpine fault). This reflects a time delay in the propagation outwards of stress associated with crustal thickening driven from the developing plate boundary. The second uplift phase matches exactly the timing of uplift in

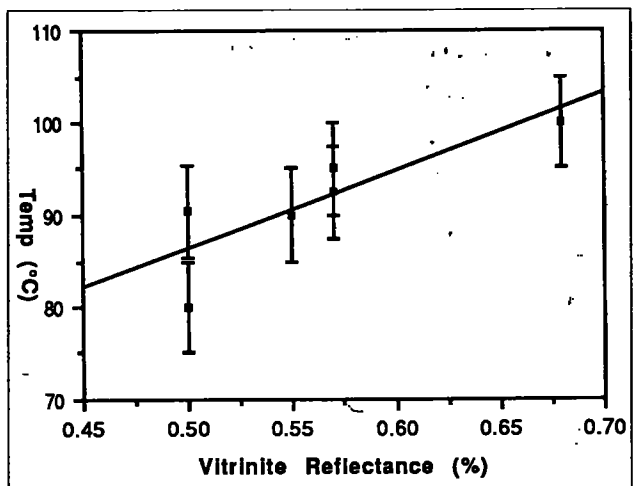


Figure 10: Plot of estimated paleotemperature ( $^\circ\text{C}$ ) versus vitrinite reflectance ( $R_o$  max %) for samples from the Rapahoe Sector of the Greymouth Coalfield.

the Hohonu Range, including Fraser Complex, east and southeast of the Grey Valley Trough and adjacent to the Alpine fault (Kamp *et al.*, in press). The timing of this uplift phase corresponds to the time when the plate boundary in South Island became obliquely compressive, and Pacific plate started to override Australia plate forming the Southern Alps (Kamp *et al.*, 1989). The third uplift phase coincides with a marked increase in the rate of uplift of the Southern Alps, which occurred at  $1.3 \pm 0.3$  Ma (Kamp *et al.*, 1989; Tippett and Kamp, submitted). The origin of this event is not really known, but it also led to the generation of much of the current topography in Westland and Buller.

### Implications for Hydrocarbon Prospectivity in West Coast

The structure of the Greymouth coalfield is typical of large parts of the West Coast region so that implications for hydrocarbon prospectivity may apply more widely.

In terms of source the Paparoa Trough contains thick and extensive coal seams of late Cretaceous and middle Eocene age that are capable of generating liquid and gas hydrocarbons as similar horizons have done in Taranaki basin. In terms of maturation, the source beds have been deeply buried and heated. Everywhere across the coalfield the source beds have been heated above  $80^\circ\text{C}$ , and above  $100^\circ\text{C}$  over most of the coalfield. These temperatures would have been experienced for at least 5 to 10 million years prior to the start of inversion.

Potential reservoirs would have to be fluvial sandstones associated with the coal seams, the thick late Eocene mudstones being the seal. In the case of the Greymouth Coalfield, but not necessarily elsewhere, the seal and indeed the potential reservoirs have been deeply eroded. Apart from the fact that in this case the structure has been breached, it was a large structure. However, the stratigraphy and fission track data show clearly that the present (compressive) structure postdated the burial that would have led to maturation: there was no trap to hold the hydrocarbons at the time they were generated. Moreover, the formation of the structure occurred episodically, involving a phase in the early Miocene, a second phase in the late Miocene, and a third phase in the Quaternary. That structure

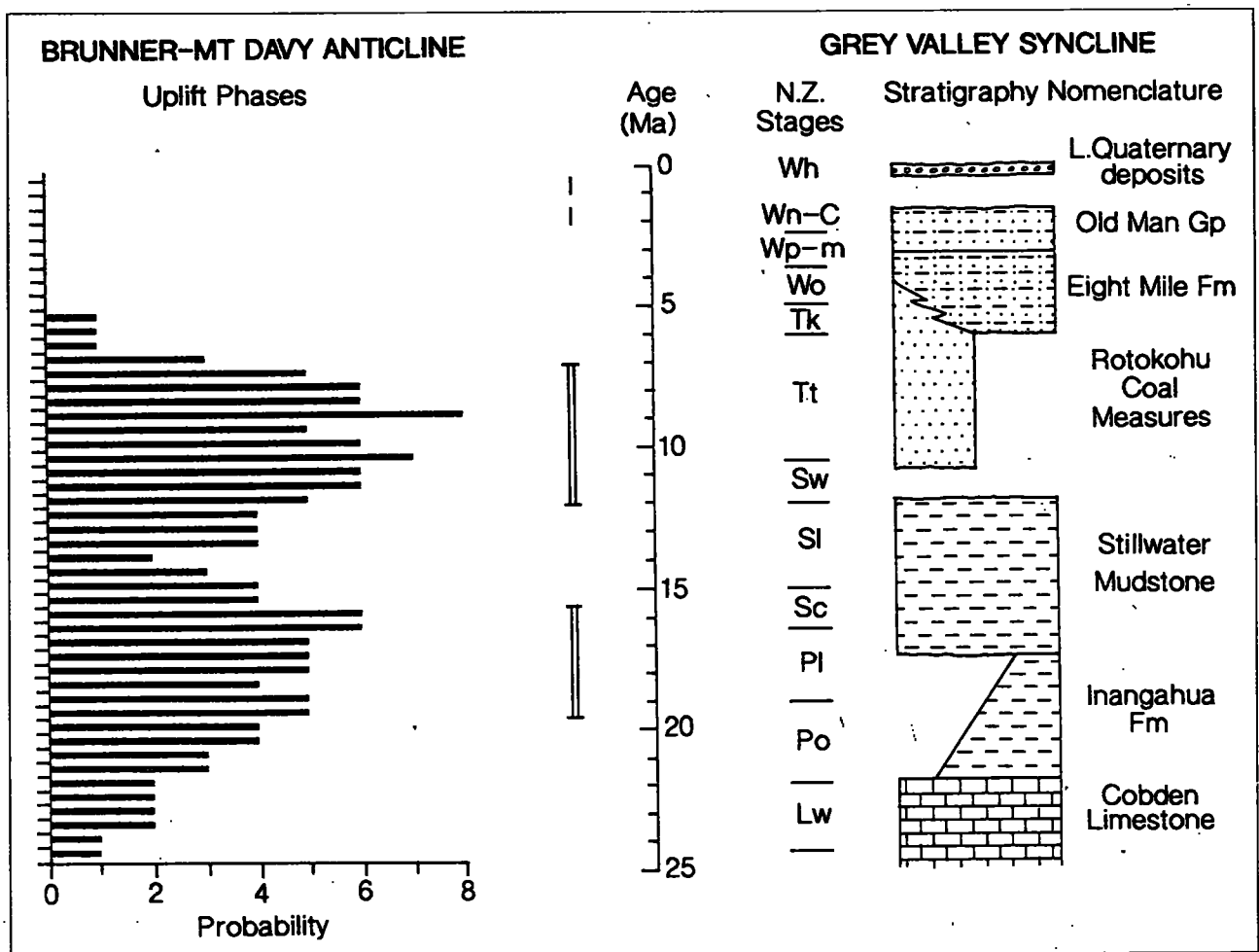


Figure 11: Diagram showing probability distribution of uplift phases in the Brunner-Mt Davy Anticline (left) versus distribution of time in the Neogene section of the western limb of the Grey Valley Syncline, based on Nathan (1978).

formation postdated maturation is possibly a widespread problem in the West Coast and in south Taranaki basin. Maximum burial in the basins that contain the coal measure source beds occurred during Paleogene rifting and thermally-controlled subsidence, and these basins were inverted during the Neogene. Because of its proximity to the plate boundary, the Brunner-Mt Davy Anticline is a particularly strongly

inverted structure, but regionally there are many identical structures of lesser size (e.g. the Cook-Fresne structures). Ideally, one needs to find coal bearing basins in the region that were slightly inverted, perhaps in the early Miocene as a result of early plate boundary movements, and subsequently reburied so that the structures were charged with hydrocarbons.

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