TAO, Vol. 13, No. 2, 109-124, June 2002

Thermo-tectonic Implications of Zircon and Apatite FT Data of the Marlborough Region, South Island, New Zealand

Ming-Hung Kao[1,*]

(Manuscript received 8 March 2001, in final form 28 March 2002)

ABSTRACT

Zircon and apatite fission track (FT) reveal some of the thermo-tectonic features of the Marlborough Region, South Island, New Zealand. The very young FT ages (<10 Ma) of zircon and apatite in the vicinity of the Alpine Fault bend and Seaward Kaikoura Range coincide with the recent rapid uplift/erosion. Four samples with reset zircon ages in the Alpine Fault bend reveal that the host rocks in this area cooled below the closure temperature of zircon (~240°C) in the late Miocene. Unlike these four zircon FT ages, most zircon FT ages are consistent with depositional ages. Annealed apatite and unannealed zircon FT ages show that the host rocks in Marlborough did not experience exposure to the closure temperature of zircon in the Mesozoic burial, but passed through the partial annealing zone (PAZ) of apatite (~60-110°C). The host rocks in the north rather than those in the south passed through the lower part of apatite PAZ. In addition, most of the zircon samples with low P(χ^2) values (<5%) show that the samples have been slightly annealed, implying that the host rocks might have experienced the upper part of the partial annealing zone of zircon (~175°C) during the Mesozoic cooling.

(Key words: FT analysis, Tectonics, Closure temperature)

1. INTRODUCTION

Fission track (FT) analysis is a useful method for establishing low-temperature thermal histories of rock successions (Naeser 1979; Laslett et al. 1987; Green et al. 1989a, b; Rohrman et al. 1994; Kao 2001).

FT data provide information about the tectonic and thermal history of host rocks. The age and cooling of host rocks may be constrained by FT analysis. FTs in U-bearing minerals such as zircon and apatite result from the spontaneous fission of ^{238}U, and can be applied to thermo-tectonic studies. Annealing of FTs is an important feature of FT analysis. If FT ages of host

[1]Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan, ROC

*Corresponding author address: Dr. Ming-Hung Kao, Institute of Earth Sciences, Academia Sinica, P.O. Box 1-55, Nankang, Taipei, Taiwan, ROC; E-mail: mhkao@earth.sinica.edu.tw

rocks were consistent with depositional ages, the distributions of single-grain FT ages would have higher P(χ^2) values (>5%), indicating that the host rocks had not experienced the partial annealing zone (PAZ) of zircon (175°C ~ 245°C) or of apatite (60°C ~ 110°C). For the annealed FT samples, the distributions of single-grain FT ages may have low P(χ^2) values (<5%).

"Closure temperature (CT)" is a concept that links the observed age to the temperature at which the FT age starts to accumulate (Dodson 1973; Hodges 1991). The closure temperature for zircon is about 240°C. The closure temperature for apatite ranges from 110°C to 125°C, depending on apatite composition (Gleadow and Duddy 1981; Green et al. 1989b). When the host rocks experience a higher temperature (>CT), FTs will be totally annealed.

Although the annealing of zircon FTs is still unknown, the kinetic of annealing in apatite (Green 1986, Green et al. 1989b; Laslett et al. 1987; Duddy et al. 1988; Crowley et al. 1991) has been established and applied to thermo-tectonic studies. Thermal histories can be reconstructed from forward modeling of time-temperature histories and comparison of predicted and measured FT ages and lengths of apatite. The aim of this article is to investigate the thermo-tectonic development of basement in Marlborough by compilation of zircon data and previously reported apatite data and the modeled thermal histories of apatite (Kao 2001).

2. GEOLOGIC SETTING

The Marlborough region (Fig. 1) is located within the Australian-Pacific plate boundary zone at a critical position between the southern end of the Hikurangi margin and the Alpine Fault section. The Torlesse Supergroup constitutes the basement of the Marlborough region. The depositional ages of basement rocks range from the Late Jurassic to Early Cretaceous, with Triassic successions in the far west. The exposure of the Alpine Schist mainly results from Neogene denudation and partly from Cretaceous denudation (Suggate 1978b). The ages of cover strata range from Cretaceous to Quaternary (Fig. 1). When Marlborough was part of a passive margin environment, early Cenozoic sequences accumulated during a tectonically quiet period which lasted from 90 to 25 Ma (Baker and Seward 1996). The Kaikoura Orogeny has followed the tectonic quiescence since the early Miocene, reflecting development of the modern Australia-Pacific plate boundary in the region (Browne 1995). Crustal shortening and strike-slip faulting are considered to have become increasingly important in this region since the Miocene (Carter and Norris 1976; Suggate 1978a; Baker and Seward 1996).

3. SAMPLING AND EXPERIMENRAL PROCEDURES

3.1 Sampling

The Marlborough region may be divided into four blocks by the Marlborough Fault System. They are: Wairau, Inland Kaikoura, Seaward Kaikoura, and Kahutara (Fig. 1). Eighty-eight samples (9414-1 to -88) were collected from outcrops along roads throughout Marlborough, or by helicopter from the Inland and Seaward Kaikoura Ranges.

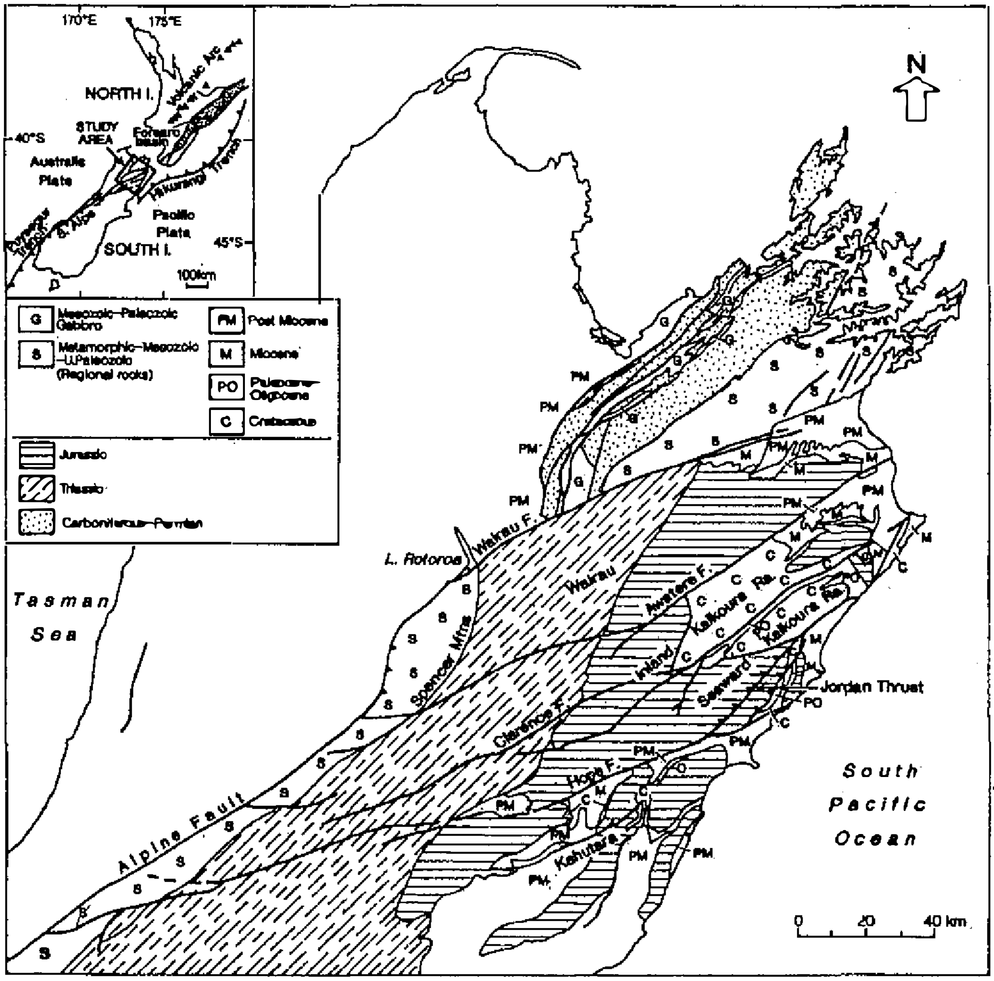

Fig. 1. Geological map of Marlborough, South Island, New Zealand (Lensen, 1962).

3.2 Experimental Procedures

The experiment procedures of this study were followed using the methods described in the papers of Green (1986), Kamp et al. (1989), Tippett and Kamp (1993), and Kao (1998). The separation of apatite concentrates from rock samples (~ 4 kg), experimental procedures, and FT dating for apatite are stated in the paper of Kao (2001). The zircon concentrates from the same rock samples were obtained by the following methods: standard magnetic and heavy liquid techniques. Zircon concentrates were mounted in FEP Teflon™ at ~ 300°C and ground to reveal internal surfaces. Once ground, zircon separates were polished with alumina slurry and then 1- μm diamond paste. The zircon mounts were etched in molten KOH-NaOH eutectic at ~ 205°C. The time of etching ranged from 16 to 56 hours. Finally, zircon mounts were cleaned by placing them in dilute HF for 1 hour.

The experimental procedures were as follows: (a) all mounts were cut to 1 x 1.5 cm and cleaned with detergent and alcohol, (b) low-uranium mica external detectors were sealed directly in contact with the mounts by using envelopes of heat-shrink plastic, (c) pinpricks were made at the corners of each mount-mica sandwich for subsequent location, (d) all mounts were stacked vertically with dosimeter glass standards (CN1 for zircons) placed at the top and bottom of each stack for irradiation. Each dosimeter was also mounted with a mica detector. Afterwards, all stacks were packed into canisters and irradiated at the X-7 facility of the HIFAR reactor, New South Wales, Australia. The nominal fluence of thermal neutrons was 3 x 10^{15} neutrons cm^{-2} for zircon.

The external detector method was applied to the FT dating (Gleadow 1981). The FT ages were determined by the zeta calibration method (Hurford and Green 1982; Green 1985). A chi-square statistic was used to assess the probability of grains counted in a sample belonging to a single population of ages (Galbraith 1981). The results of weighted mean zetas are reported in Table 1: zircon weighted mean $\zeta = 140.2 \pm 3.6$ (CN1).

4. FT RESULTS AND DISCUSSIONS

4.1 Zircon FT Results

The distribution of zircon FT ages is illustrated in Fig. 2. Except for a few samples of poor zircon concentrates, zircon FT results of the Marlborough samples are shown in Table 2 and Figs. 3-6. Transects T1, T2, T3, and T4 are located within four blocks, respectively (Fig. 2). Uncertainties of FT ages are reported at the 1s level. Zircon ages of the samples range from 6.8 ± 0.5 to 336.2 ± 45.3 Ma.

4.1.1 Wairau transect (T1)

Upper Triassic-Jurassic sandstone (greywacke) constitutes mainly the basement of the Waiaru block. The cover strata are of the late Miocene and late Quaternary. Samples 9414-19, -20, -21 and –25 (Fig. 2), lying in the vicinity of the Alpine Fault bend, have very young FT ages (<10 Ma) of zircon (Table 2), indicating that they have experienced the closure temperature of zircon (~240°C). These FT ages can be correlated with recent rapid uplift/erosion in this area. Excluding these four samples, the zircon FT ages of thirteen samples (Table 2 and Fig. 3) in the Waiaru block are consistent with the depositional ages. The zircon FT ages (> 250 Ma) of the rest of the samples are older than the depositional ages, showing that they can be correlated with the source provenance. According to these FT data, the samples of the host rocks in this block have been slightly annealed and might have passed through the upper part of the zircon PAZ (~175°C) in the Mesozoic denudation.

4.1.2 Inland Kaikoura transect (T2)

Twelve samples of this transect were collected from the Inland Kaikoura Range which lies between the Awatere and Clarence Faults (Figs. 1 and 2). The stratigraphic units of the

Table 1. Results of calibration of fission track age determinations by the zeta approach.

Age Standard and Irradiation No.	Mineral (No. of crystals)	Spontaneous ρ_s	N_s	Induced ρ_i	N_i	$P(\chi^2)$ %	Glass	Dosimeter ρ	N_d	$\zeta \pm 1\sigma$
Buluk wk029	Zircon (20)	0.712	169	2.208	524	100	CN1	0.8772	2169	114.7 ± 10.5
Buluk pt845	Zircon (20)	1.181	369	1.757	549	100	U 3	0.4926	1218	98.0 ± 7.3
Tardree wk029	Zircon (20)	5.168	782	4.818	729	100	CN1	0.8772	2193	123.9 ± 7.3
Tardree wk029	Zircon (20)	5.192	914	5.003	886	100	CN1	0.8972	2218	127.4 ± 70.0
Tardree pt845	Zircon (20)	5.411	869	2.208	524	100	CN1	0.8772	2169	114.7 ± 10.5
Mt Dromedary wk029	Zircon (13)	12.843	724	6.652	375	99	CN1	0.9072	2240	113.6 ± 7.6
Mt Dromedary wk029	Zircon (17)	14.264	1058	8.170	606	100	CN1	0.9172	2264	124.2 ± 6.9
Mt Dromedary pt845	Zircon (10)	11.994	949	2.958	234	100	U3	0.4926	1218	99.6 ± 7.8
Mt Dromedary pt845	Zircon (10)	12.354	672	2.978	162	100	U3	0.4926	1218	97.3 ± 9.0
Mt Dromedary pt846	Zircon (15)	13.891	1154	3.479	289	100	U3	0.4930	1219	101.0 ± 7.3
Mt Dromedary pt846	Zircon (15)	14.720	1252	3.692	314	100	U3	0.4930	1219	101.2 ± 7.0
Mt Dromedary pt846	Zircon (20)	12.464	1319	3.071	325	100	U3	0.4930	1219	99.4 ± 6.8
Fish Canyon wk029	Zircon (20)	4.067	739	9.597	1739	99.7	CN1	0.9272	2291	141.8 ± 5.4
Fish Canyon pt845	Zircon (20)	4.112	1822	3.631	1609	32.4	U3	0.4926	1218	99.9 ± 5.1
Fish Canyon pt845	Zircon (20)	5.023	2126	4.536	1920	100	U3	0.4926	1218	102.2 ± 5.1
Fish Canyon pt846	Zircon (13)	4.135	773	3.713	649	100	U3	0.4930	1219	101.5 ± 6.6
Mt Warning wk029	Zircon (10)	3.198	272	8.595	731	98.8	CN1	0.9672	2387	126.9 ± 9.8
Mt Warning pt845	Zircon (20)	4.382	910	4.227	878	97.1	U3	0.4926	1218	89.5 ± 5.3
Mt Warning pt845	Zircon (13)	5.009	426	4.327	368	97.1	U3	0.4926	1218	80.1 ± 6.4
Mt Warning pt846	Zircon (13)	4.065	595	4.024	589	100	U3	0.4930	1219	91.7 ± 3.6
								Zircon Mean ζ		140.2 ± 3.6

Analyses of zircon age standards are by external detector method; track densities (ρ) are (x106 cm^{-2}); N is number of tracks counted. $P(\chi^2)$ is the probability of obtaining χ^2 value for ν degrees of freedom where ν = (Number of crystals-1) [Galbraith 1981]; pooled ρ_s/ρ_i ratio used to calculate ζ and uncertainty where $P(\chi^2)$>5%; mean ρ_s/ρ_i ratio used to calculate ζ and uncertainty where $P(\chi^2)$>5% [Green 1981]. Standard ages used are Fish Canyon Tuff 27.8 ± 0.7 Ma, Tardree Rhyolite 58.7 ± 1.1 Ma [Hurford and Green 1983]; Mount Dromedary Igneous Complex 98.7 ± 0.6 Ma, Mount Warning Complex 22.8 ± 0.5 Ma [Green 1985]; Buluk Member tuff 16.2 ± 0.2 Ma [Hurford and Watkins 1987]. An uncertainty component from the independent age is included in the error on each ζ value; zircon mean ζ and its error weighted according to uncertainties on individual ζ values. Zircon ζ determinations fulfill the requirements proposed by Hurford [1990]. Zircon mean ζ calculated for CN1, with U3 sample determinations being converted to CN1 terms by using the factor of Green [1985].

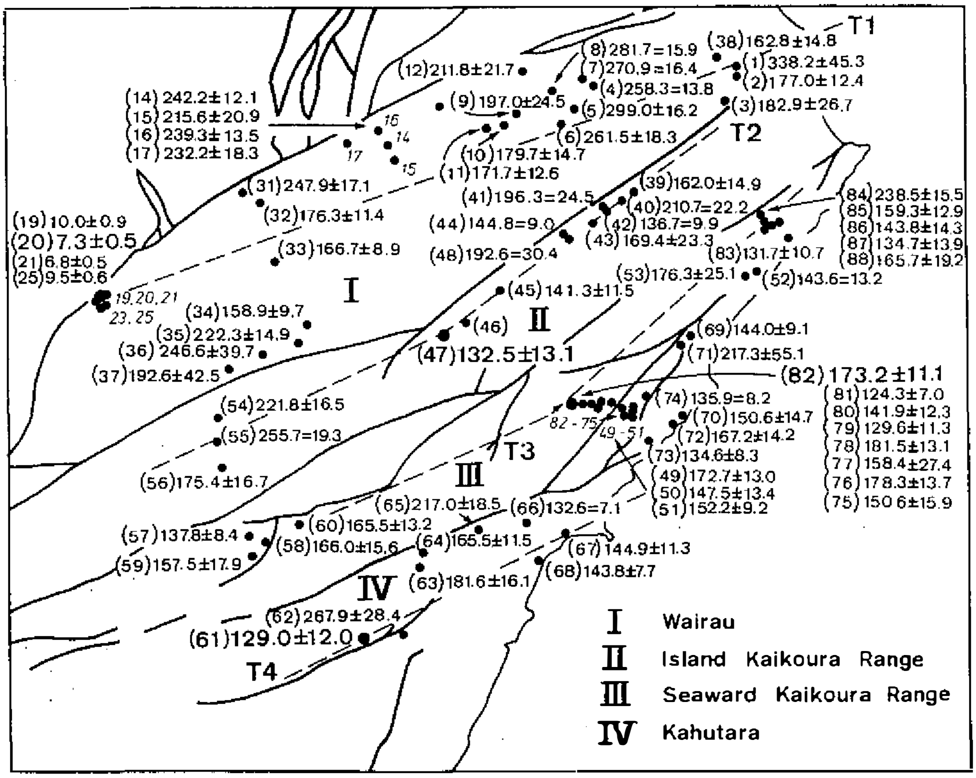

Fig. 2. Distribution of zircon fission track ages (given in Ma) in Marlborough. Four major blocks, designated I, II, III, and IV in the Marlborough region are shown. The main faults whose names are given in Fig. 1 are indicated by solid lines. Four transects (T1, T2, T3, and T4) shown in long-dashed lines are located within the four major blocks, respectively. The sample numbers with their prefix 9414- omitted are shown in parentheses.

basement in the Inland Kaikoura block are similar to those of the Wairau block. The depositional ages of cover strata range from Cretaceous to Quaternary. Most zircon FT ages of the samples are in accordance with the depositional ages (from Triassic to Jurassic) (Table 2 and Fig. 4), implying that the host rocks have not experienced the PAZ of zircon (175°C ~ 245°C). In addition, most host rock samples in this block are low in P(χ^2) values (<5%) (Table 2), showing that they might have experienced the upper part of the zircon PAZ (~175°C) during the Mesozoic denudation.

4.1.3 Seaward Kaikoura transect (T3)

The stratigraphic units of the basement in the Seaward Kaikoura block are the same as those of the Inland Kaikoura block (Fig. 1). Except Sample 9414-84, most zircon FT ages

Table 2. Zircon fission track data for Marlborough samples.

Sample Number	Location Easting	Location Northing	Ele. (m)	Mineral	No of Cry.	Spontaneous ρ_s	Spontaneous N_s	Induced ρ_i	Induced N_i	$P(\chi^2)$ %	Mean ratio ρ_s/ρ_i	ρ_d (E+6)	N_d	Age (Ma) ± 1σ	Sub-Region	Transect
9414-01	2591300	5955000	220	zircon	15	17.353	2008	4.062	470	<0.1	4.724 ± 0.419	1.191	2711	336.2 ± 45.3	Wairau	T1
9414-02	2590500	5952900	300	zircon	16	10.299	171	4.801	793	<0.1	2.198 ± 0.141	1.201	2760	177.0 ± 12.4	Wairau	T1
9414-03	2587700	5946200	480	zircon	5	27.555	549	12.791	253	0.2	2.392 ± 0.411	1.206	2784	182.9 ± 26.7	Wairau	T1
9414-04	2564500	5949400	120	zircon	20	13.098	2254	4.219	726	23.2		1.211	2809	258.3 ± 13.8	Wairau	T1
9414-05	2560300	5943900	300	zircon	20	12.745	2395	3.550	667	60.2		1.216	2834	299.0 ± 16.2	Wairau	T1
9414-06	2557700	5938500	500	zircon	20	10.866	1612	3.424	508	1.8	3.220 ± 0.185	1.221	2859	261.5 ± 18.3	Wairau	T1
9414-07	2563200	5951800	220	zircon	20	12.639	1600	3.926	497	66.3		1.226	2883	270.9 ± 16.4	Wairau	T1
9414-08	2557500	5949300	300	zircon	20	13.298	1999	3.985	599	9.7		1.231	2908	281.7 ± 15.9	Wairau	T1
9414-09	2550700	5944900	320	zircon	20	12.176	2023	5.302	881	<0.1	2.485 ± 0.177	1.236	2932	197.0 ± 24.5	Wairau	T1
9414-10	2545200	5941400	420	zircon	20	9.428	1725	4.515	826	<0.1	2.344 ± 0.225	1.241	2957	179.7 ± 14.7	Wairau	T1
9414-11	2548200	5941600	400	zircon	20	11.337	1581	5.760	804	<0.1	2.133 ± 0.168	1.251	3006	171.7 ± 12.6	Wairau	T1
9414-12	2553000	5956000	240	zircon	6	14.075	362	5.756	148	41.6		1.256	3031	211.8 ± 21.7	Wairau	T1
9414-14	2526800	5940500	480	zircon	20	15.161	2489	5.452	895	21.7		1.266	3080	242.2 ± 12.1	Wairau	T1
9414-15	2528200	5936900	520	zircon	12	15.416	1174	6.264	477	<0.1	2.604 ± 0.237	1.271	3105	215.6 ± 20.9	Wairau	T1
9414-16	2525700	5945400	420	zircon	20	13.083	1695	4.801	622	8.6		1.276	3129	239.3 ± 13.5	Wairau	T1
9414-17	2519600	5943900	380	zircon	12	11.910	695	4.524	264	54.3		1.281	3154	232.2 ± 18.3	Wairau	T1
9414-19	2470900	5908200	460	zircon	20	2.146	348	11.310	1835	<0.1	0.193 ± 0.002	0.756	1870	10.0 ± 0.9	Wairau	T1
9414-20	2470600	5908200	440	zircon	20	1.575	282	11.876	2126	6.2		0.783	1939	7.3 ± 0.5	Wairau	T1
9414-21	2470600	5908200	440	zircon	20	1.583	252	13.580	2162	32		0.836	2070	6.8 ± 0.5	Wairau	T1
9414-25	2469800	5909300	540	zircon	20	1.846	336	11.730	2134	77.9		0.826	2136	9.5 ± 0.6	Wairau	T1
9414-31	2498800	5933600	700	zircon	10	23.782	1176	7.098	351	11.1		1.076	2662	247.9 ± 17.1	Wairau	T1
9414-32	2504400	5932500	620	zircon	10	13.298	1039	5.747	449	7.5		1.102	2728	176.3 ± 11.4	Wairau	T1
9414-33	2500900	5914700	800	zircon	20	12.471	1739	5.844	815	61.5		1.129	2794	166.7 ± 8.9	Wairau	T1
9414-34	2504300	5904400	980	zircon	15	14.853	1087	7.474	547	6.4		1.155	2960	158.9 ± 9.7	Wairau	
9414-35	2503300	5902500	940	zircon	11	15.281	1073	5.597	393	47.2		1.182	2926	222.3 ± 14.9	Wairau	
9414-36	2496800	5895800	920	zircon	11	17.331	857	5.865	290	<0.1	3.562 ± 0.556	1.209	2992	246.6 ± 39.7	Wairau	
9414-37	2491500	5890700	1040	zircon	5	12.032	238	5.662	112	0.2	2.815 ± 0.749	1.235	3057	192.6 ± 42.5	Wairau	
9414-38	2587700	5959100	60	zircon	20	10.291	1693	5.630	941	<0.1	2.101 ± 0.207	1.262	3120	162.8 ± 14.8	Wairau	T1
9414-39	2573400	5931600	400	zircon	18	10.580	1444	4.968	678	<0.1	2.359 ± 0.224	1.108	2738	162.0 ± 14.9	In. Kaikoura	T2

(Table 2. continued)

Sample Number	Location Easting	Location Northing	Ele. (m)	Mineral	No of Cry.	Spontaneous ρ_s	Spontaneous N_s	Induced ρ_i	Induced N_i	$P(\chi^2)$ %	Mean ratio ρ_s/ρ_i	ρ_d (E+6)	N_d	Age (Ma) ± 1σ	Sub-Region	Transect
9414-40	2570800	5929800	400	zircon	6	9.645	372	3.526	136	20.1		1.117	2761	210.7 ± 22.2	In. Kaikoura	T2
9414-41	2567600	5927700	400	zircon	10	10.900	636	4.182	244	0.3	2.746 ± 0.296	1.127	2785	196.3 ± 24.5	In. Kaikoura	T2
9414-42	2567700	5927600	400	zircon	20	8.558	1515	5.005	886	<0.1	1.900 ± 0.161	1.136	2809	136.7 ± 9.9	In. Kaikoura	T2
9414-43	2564700	5925500	400	zircon	10	8.241	595	3.837	277	<0.1	2.410 ± 0.286	1.146	2833	169.4 ± 23.3	In. Kaikoura	T2
9414-44	2558900	5923500	510	zircon	20	8.740	994	4.836	550	43.2		1.156	2856	144.8 ± 9.0	In. Kaikoura	T2
9414-45	2544900	5911900	1280	zircon	20	8.905	1418	5.024	800	<0.1	1.904 ± 0.183	1.166	2880	141.3 ± 11.5	In. Kaikoura	T2
9414-47	2532300	5903300	900	zircon	20	11.698	995	7.160	609	<0.1	1.715 ± 0.202	1.185	2927	132.5 ± 13.1	In. Kaikoura	T2
9414-48	2559100	5923500	500	zircon	12	10.066	667	4.376	290	<0.1	2.101 ± 0.207	1.195	2951	192.6 ± 30.4	In. Kaikoura	T2
9414-49	2570200	5886800	620	zircon	20	8.426	75	5.370	887	<0.1	2.343 ± 0.229	1.205	2974	172.7 ± 13.0	Sea. Kaikoura	T3
9414-50	2570300	5886300	640	zircon	20	10.203	1675	5.774	948	<0.1	1.931 ± 0.187	1.215	2998	147.5 ± 13.4	Sea. Kaikoura	T3
9414-51	2570400	5885700	460	zircon	20	10.100	1738	5.645	973	0.3	1.891 ± 0.125	1.224	3022	152.2 ± 9.2	Sea. Kaikoura	T3
9414-52	2591800	5914600	70	zircon	7	6.320	361	5.176	215	55.6		1.234	3046	143.6 ± 13.2	Sea. Kaikoura	T3
9414-53	2591600	5915000	120	zircon	10	8.999	712	4.386	347	<0.1	2.450 ± 0.443	1.243	3070	176.3 ± 25.1	Sea. Kaikoura	T3
9414-54	2491200	5879500	1040	zircon	16	13.104	1620	5.080	628	0.2	2.748 ± 0.241	1.253	3093	221.8 ± 16.5	In. Kaikoura	T2
9414-55	2492300	5873100	900	zircon	13	11.096	1284	3.820	442	3.6	3.143 ± 0.225	1.263	3117	255.7 ± 19.3	In. Kaikoura	T2
9414-56	2493100	5865100	840	zircon	10	8.922	803	4.578	412	0.7	2.177 ± 0.231	1.272	3141	175.4 ± 16.7	In. Kaikoura	T2
9414-57	2498200	5861600	800	zircon	10	10.245	922	6.600	594	11.0		1.280	3165	137.8 ± 8.4	Sea. Kaikoura	T3
9414-58	2500000	5856400	700	zircon	16	8.243	1125	3.488	476	<0.1	2.491 ± 0.256	1.050	2595	166.0 ± 15.6	Sea. Kaikoura	T3
9414-59	2502500	5861100	760	zircon	18	6.962	1267	3.116	567	<0.1	2.588 ± 0.348	1.054	2605	157.5 ± 17.9	Sea. Kaikoura	T3
9414-60	2505800	5867300	780	zircon	16	11.177	1647	4.954	730	<0.1	2.416 ± 0.199	1.058	2615	165.5 ± 13.2	Kahutara	T3
9414-61	2520200	5839900	110	zircon	20	10.384	1941	5.692	1064	<0.1	1.960 ± 0.207	1.062	2624	129.0 ± 12.0	Kahutara	T4
9414-62	2527900	5840000	140	zircon	10	13.016	1210	3.399	316	0.2	3.933 ± 0.512	1.066	2634	267.9 ± 28.4	Kahutara	T4
9414-63	2532400	5860500	360	zircon	20	9.786	1684	3.789	652	<0.1	2.700 ± 0.252	1.070	2644	181.6 ± 16.1	Kahutara	T4
9414-64	2503100	5863000	400	zircon	20	8.572	1526	3.910	696	0.3	2.423 ± 0.175	1.073	2654	165.5 ± 11.5	Kahutara	T4
9414-65	2543600	5868300	280	zircon	20	11.463	2120	4.099	758	<0.1	3.065 ± 0.262	1.077	2664	217.0 ± 18.5	Kahutara	T4
9414-66	2551700	5867700	100	zircon	20	8.245	1476	4.665	835	54.4		1.081	2674	132.6 ± 7.1	Kahutara	T4
9414-67	2558400	5863300	20	zircon	20	11.603	2100	5.951	1077	<0.1	2.100 ± 1.910	1.085	2683	144.9 ± 11.3	Kahutara	T4
9414-68	2553400	5858000	20	zircon	15	12.329	1573	6.474	826	14.8		1.089	2693	143.8 ± 7.7	Kahutara	T4
9414-69	2578500	5902200	150	zircon	20	11.022	1875	5.743	977	<0.1	1.991 ± 0.148	1.093	2703	144.0 ± 9.1	Kahutara	T3

(Table 2. continued)

Sample Number	Location Easting	Location Northing	Ele. (m)	Mineral	No of Cry.	Spontaneous ρ_s	Spontaneous N_s	Induced ρ_i	Induced N_i	$P(\chi^2)$ %	Mean ratio ρ_s/ρ_i	ρ_d (E+6)	N_d	Age (Ma) $\pm 1\sigma$	Sub-Region	Transect
9414-70	2580700	5886600	20	zircon	15	10.514	1331	5.158	653	<0.1	2.038 ± 0.097	1.097	2713	150.6 ± 14.7	Sea. Kaikoura	T3
9414-71	2578200	5902200	150	zircon	3	13.145	221	4.580	77	0.4	3.328 ± 1.048	1.101	2723	217.3 ± 55.1	Sea. Kaikoura	T3
9414-72	2578600	5884200	40	zircon	20	12.48	2086	5.666	947	<0.1	2.402 ± 0.206	1.105	2732	167.2 ± 14.2	Sea. Kaikoura	T3
9414-73	2573000	5880600	40	zircon	20	9.218	1951	5.339	1130	<0.1	1.861 ± 0.124	1.109	2742	134.6 ± 8.3	Sea. Kaikoura	T3
9414-74	2573000	5889500	420	zircon	15	9.214	1048	5.231	595	11.3		1.112	2752	135.9 ± 8.2	Sea. Kaikoura	T3
9414-75	2568600	5886500	1200	zircon	20	13.067	2184	6.767	1131	<0.1	0.256 ± 0.240	1.116	2762	150.6 ± 15.9	Sea. Kaikoura	T3
9414-76	2567700	5886800	1560	zircon	20	13.739	2473	5.833	1050	<0.1	2.475 ± 0.189	1.120	2772	178.3± 13.7	Sea. Kaikoura	T3
9414-77	2566300	5888100	2200	zircon	12	15.239	1452	8.816	837	<0.1	2.134 ± 0.294	1.125	2781	158.4 ± 27.4	Sea. Kaikoura	T3
9414-78	2564500	5887600	2300	zircon	20	9.870	1845	3.649	682	<0.1	2.828 ± 0.228	0.988	2443	181.5 ± 13.1	Sea. Kaikoura	T3
9414-79	2563800	5886800	2200	zircon	5	9.509	442	5.099	237	30.8		1.001	2476	129.6 ± 11.0	Sea. Kaikoura	T3
9414-80	2562800	5886900	2400	zircon	17	10.097	1408	4.977	694	<0.1	2.120 ± 0.199	1.014	2508	141.9 ± 12.31	Sea. Kaikoura	T3
9414-81	2561200	5887100	2600	zircon	20	9.578	1885	5.594	1101	<0.1	1.897 ± 0.165	1.027	2541	124.3 ± 7.6	Sea. Kaikoura	T3
9414-82	2558700	5887000	1780	zircon	12	11.043	1114	4.590	463	19.6		1.041	2574	173.2 ± 11.0	Sea. Kaikoura	T3
9414-83	2600100	5924000	60	zircon	7	9.878	508	5.483	282	9.2		1.054	2607	131.7 ± 10.7	Sea. Kaikoura	T3
9414-84	2599000	5928900	160	zircon	20	14.315	1345	4.406	414	25.2		1.067	2639	238.5 ± 15.5	Sea. Kaikoura	T3
9414-85	2596500	5928800	220	zircon	20	10.410	1884	4.857	879	<0.1	2.301 ± 0.179	1.080	2672	159.3 ± 12.9	Sea. Kaikoura	T3
9414-86	2596400	5930300	300	zircon	20	15.386	2602	7.900	1336	<0.1	2.181 ± 0.252	1.093	2705	143.8 ± 14.3	Sea. Kaikoura	T3
9414-87	2597700	5928600	380	zircon	10	10.473	935	6.182	538	<0.1	1.875 ± 0.197	1.107	2737	134.7 ± 13.9	Sea. Kaikoura	T3
9414-88	2598700	5928700	260	zircon	10	9.284	686	4.314	320	0.1	2.297 ± 0.230	1.120	2770	165.7 ± 19.2	Sea. Kaikoura	T3

Easting and northing refer to New Zealand Map Series 260. Track densities (ρ) are $\times 10^6$ tracks cm^{-2}. All analyses are by external detector method using 0.5 for the $4\pi/2\pi$ geometry correction factor. Zircon ages calculated using dosimeter glass CN1 and zeta-CN1 = 140.2 ± 3.6 (1σ). $P(\chi^2)$ is probability of obtaining χ^2 value for ν degrees of freedom (where ν is number of crystals - 1) [Galbraith 1981]; pooled ρ_s/ρ_i ration is used to calculate age and uncertainty where $P(\chi^2)>5\%$; mean ρ_s/ρ_i ration is used to calculate age and uncertainty where $P(\chi^2)<5\%$ [Green 1981]. Ele.: elevation (m); Cry.: crystals; In.: Inland; Sea.: Seaward.

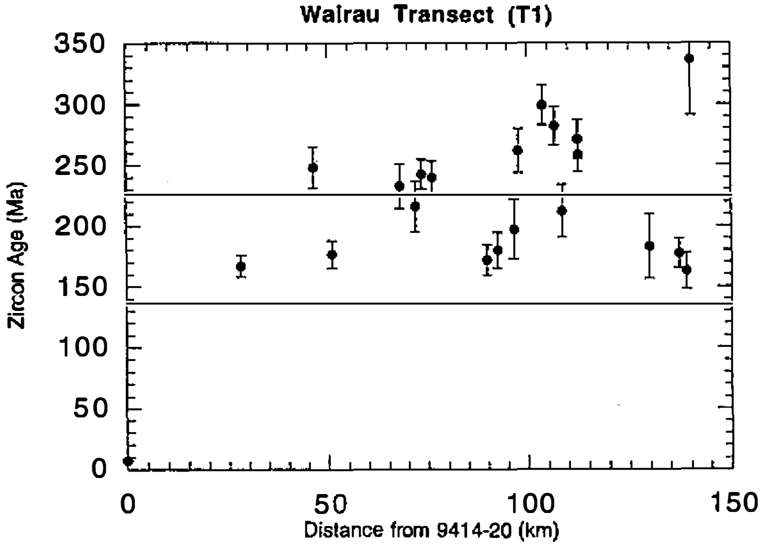

Fig. 3. Zircon fission track ages versus distance from Sample 9414-20 along Transect T1. The area between two horizontal lines is the depositional age (from Triassic to Jurassic). Samples 9414-34, -35, -36, and -37 are excluded.

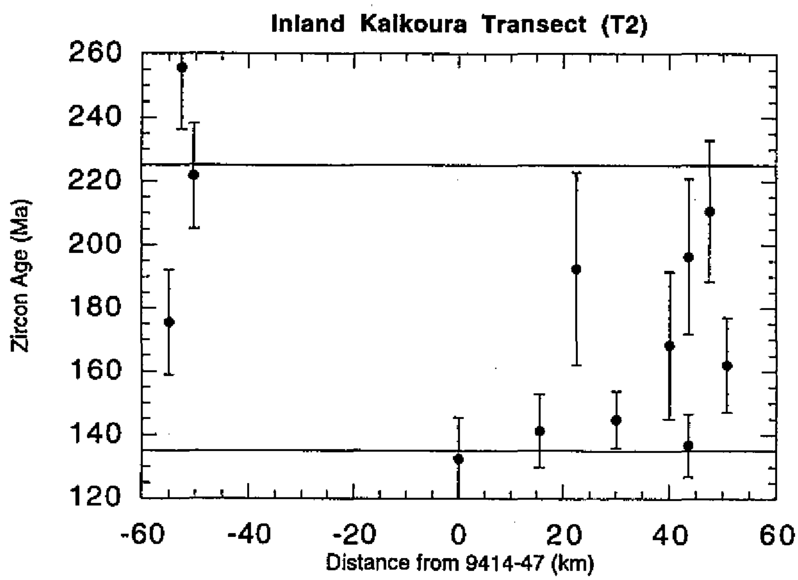

Fig. 4. Zircon fission track ages versus distance from Sample 9414-47 along Transect T2; the area between two horizontal lines is the depositional age (from Triassic to Jurassic). The distance is arbitrarily designated as positive for the samples northeast from Sample 9414-47, and as negative for the samples southwest from Sample 9414-47.

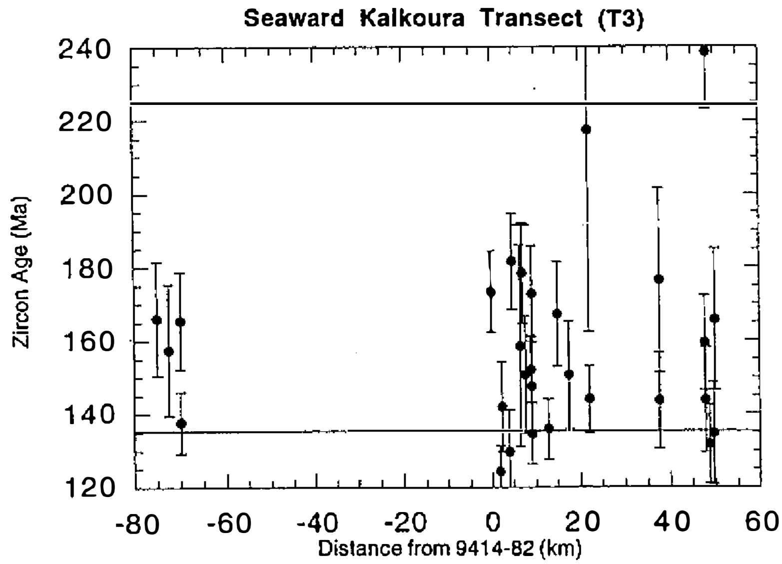

Fig. 5. Zircon fission track ages versus distance from Sample 9414-82 along Transect T3; the area between two horizontal lines is the depositional age (from Triassic to Jurassic). The distance is arbitrarily designated as positive for the samples northeast from Sample 9414-82, and as negative for the samples southwest from Sample 9414-82.

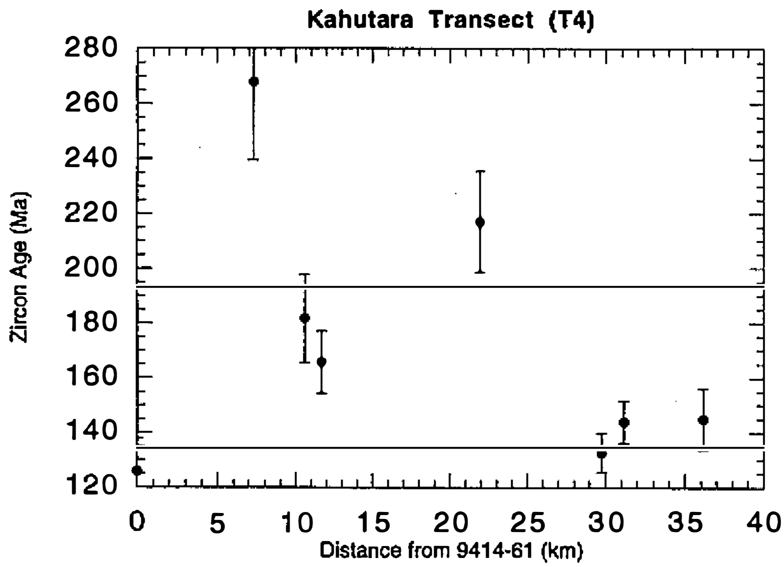

Fig. 6. Zircon fission track ages versus distance from Sample 9414-61 along Transect T4; the area between two horizontal lines is the depositional age (Jurassic).

(Table 2 and Fig. 5) are consistent with the depositional ages (from Triassic to Jurassic), reflecting that the host rocks have not passed through the PAZ of zircon. Samples 9414-79 and 81 with young zircon FT ages (~124-129 Ma) indicate that they have been annealed. Similar to those of the Inland Kaikoura transect, most host rock samples are low in P(χ^2) values (<5%), reflecting that they might have also passed through the upper part of the zircon PAZ (~175°C) during the Mesozoic cooling.

4.1.4 Kahutara transect (T4)

Eight samples (9414-61 to –68) were collected from south of the Hope Fault (Figs. 1 and 2), and belong to Jurassic depositional ages. Sample 9414-61 with a young zircon FT age (~129 Ma) (Table 2 and Fig. 6) indicates that it experienced the PAZ of zircon. Except for Samples 9414-62 and –65, the zircon FT ages of the samples (Table 2 and Fig. 6) in the Kahutara block are consistent with the depositional age, reflecting that the host rocks have not passed through the PAZ of zircon. In brief, the samples in this block might be slightly annealed. The older zircon FT ages (>200 Ma) (Samples 9414-62 and –65) may be related to the source provenance of the sediments.

4.2 Apatite Results

Modeled thermal histories (Fig. 7) of apatite samples with good length data were reported in the paper of Kao (2001). The modeled thermal histories indicate two major cooling events: the earlier one occurring in the mid-Cretaceous (~100 Ma) and the later one lasting from the early Miocene (~20 Ma) to the present. Annealed apatite FT data show that the host rocks experienced the PAZ of apatite. The timing of the main Neogene uplift/erosion event was earlier (mid to late Miocene) in the Wairau block than that in the place to the southeast of the Seaward Kaikoura Range (late Pliocene-Pleistocene). The modeled thermal histories of the samples collected from Kaikoura Ranges reflect the continuance of the cooling event from Pliocene to the present. In addition, the samples in the north Marlborough rather than those in the south experienced partial annealing in the lower part of the apatite PAZ.

4.3 Interpretation

Significant thermo-tectonic implications can be discussed in the light of the apatite and zircon FT data presented above.

The extremely young zircon ages (~6.8-10.0 Ma) of the samples (9414-19, -20, -21 and -25) lying in the vicinity of the Alpine Fault bend reveal that the FTs have been reset during the recent rapid uplift and experienced cooling from temperatures of ~240°C, the closure temperature of zircon. Except for these reset samples, most of the zircon ages are consistent with the stratigraphic ages. In addition, there are three samples (9414-61, -79 and –81) with zircon ages (124-129 Ma) younger than the stratigraphic ages, showing that the samples have been slightly annealed. The host rocks passed through the upper part of the partial annealing zone of zircon (~175°C) during the Mesozoic denudation.

The results of apatite and zircon FT data (Figs. 3-7) can model thermal histories of the

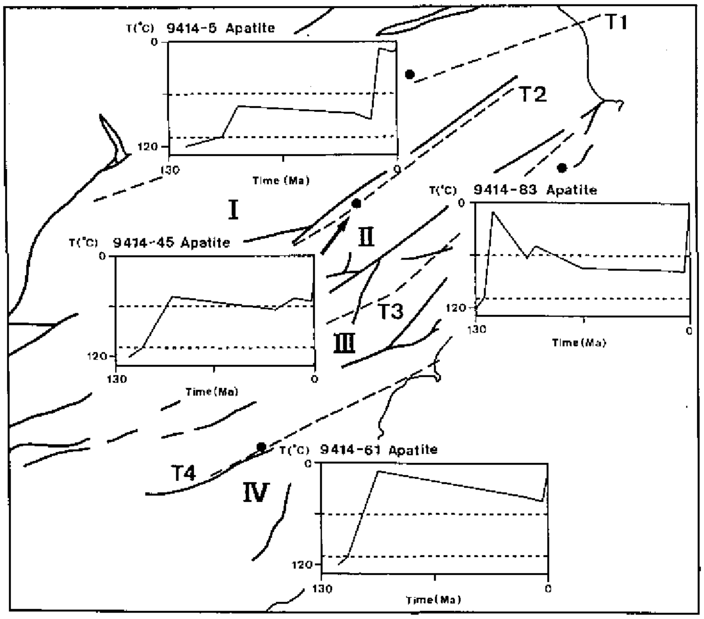

Fig. 7. Modeled thermal histories of Marlborough, established by the apatite fission track data (modified from Kao 2001). The area between two short-dashed lines is the apatite partial annealing zone (PAZ).

four blocks in Marlborough as shown in Fig. 8. Thermal histories in different blocks show different patterns of temperature-time paths, implying that each block has experienced its own thermo-tectonic history. Except those in the vicinity of the Alpine Fault bend, most of the host rocks in Marlborough have not experienced exposure to the closure temperature of zircon in the Mesozoic burial, but passed through the partial annealing zone (PAZ) of apatite.

4.4 Correlation with Other Geologic Events

Apatite and Zircon FT data show that there were two major cooling events, the earlier one occurring in the mid-Cretaceous (~100 Ma) and the later one expanding from the early Miocene (~20 Ma) to the present.

The earlier cooling event can be correlated with a magmatic and extension event that occurred around ~100 Ma in this region, as supported by the following evidence: (a) the Rb-Sr and FT ages of an igneous pluton, forming the peaks of the Inland Kaikoura Range, range from 105 to 93 Ma (Baker and Seward 1996), (b) one formation (105-100 Ma) unconformably overlies Torlesse basement (Reay 1993), and (c) terrestrial sediments (94-100 Ma) overlies a marine fan delta sequence, showing an end of a regress event (Reay 1993). The later cooling event (~20 Ma) can be correlated with the sedimentation of the Great Marlborough Conglomerate (Browne 1995) which indicates rapid uplift and erosion during the early Miocene (~20 Ma). Thrusting and shortening deformation became dominant during the late Cenozoic Kaikoura Orogeny. The initial movements of the Marlborough Fault System can be related to the Great Marlborough Conglomerate (Browne 1995).

Apatite and Zircon FT ages (<10 Ma) of the host rocks in the vicinity of the Alpine Fault bend coincide with the recent rapid uplift/erosion, related to the continuation of Kaikoura

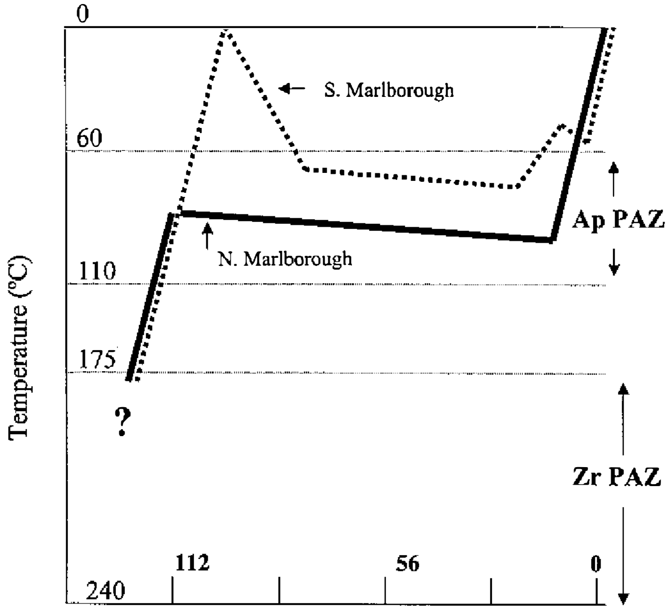

Fig. 8. Modeled thermal histories of the Marlborough region, assessed by zircon and apatite fission track data in the present study. The solid and dotted lines indicate the modeled thermal histories of the northern and southern parts of the Marlborough region, respectively. Ap: apatite; Zr: zircon; PAZ: partial annealing zone.

Orogeny. The temperature-time path in the Marlborough region modeled by zircon and apatite FT data (Fig. 8) shows the thermo-tectonic characters of two major cooling events in the present region.

5. CONCLUSIONS

The young ages (<10 Ma) of zircon in the vicinity of the Alpine Fault bend can be correlated with the recent rapid uplift/erosion in this area. Most of the zircon FT ages are consistent with depositional ages. Three samples, collected from the SE Marlborough (Seaward Kaikoura Range and Kahutara areas), have younger zircon ages (< depositional ages), indicating that the host rocks in SE Marlborough have experienced exposure to the temperatures close to the upper zone of partial annealing for zircon (~175°C) and cooled in the late Mesozoic denudation. In addition, the zircon and apatite FT data show that the host rocks in Marlborough have not experienced exposure to the PAZ of zircon in the Mesozoic burial, but passed through the PAZ of apatite. Each of the four blocks in Marlborough has experienced different temperature-time paths since the late Mesozoic cooling. The host rocks in the north rather than those in the south passed through the lower part of apatite PAZ.

Acknowledgements The author would like to express thanks to Professor Peter Kamp of The University of Waikato for his guidance and support. The experimental work was completed at the Fission Track Laboratory of the Earth Sciences Department, University of Waikato, New Zealand. The author is also grateful to Frank Bailey for his kindness and encouragement. Thanks are due to Research Fellows, H.C. Chiu and T.F. Yui, the Institute of Earth Sciences, Academia Sinica, for their enthusiastic help and encouragement. In addition, the author appreciates three anonymous reviewers for their suggestions and comments. This manuscript was written up whilst the author was a postdoctoral fellow at the Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan during 2001.

REFERENCES

Baker, J., and D. Seward, 1996: Timing of Cretaceous extension and Miocene compression in northeast South Island, New Zealand: Constraints from Rb-Sr and fission-track dating of an igneous pluton. *Tectonics*, **15**, 976-983.

Browne, G. H., 1995: Sedimentation patterns during the Neogene in Marlborough, New Zealand. *J. Roy. Soc. New Zealand*, **4**, 459-483.

Carter, R. M., and R. J. Norris, 1976: Cainozoic history of Southern New Zealand: An accord between geological observations and plate tectonic predictions. *Earth and Planet. Sci. Lett.*, **31**, 85-94.

Crowley, K. D., M. Cameron, and R. L. Schaeffer, 1991: Experimental studies of annealing of etched fission tracks in fluorapatite. *Geochimica et Cosmochimica Acta*, **55**, 1449-1465.

Dodson, M. H., 1973: Closure temperature in cooling geochronological and petrological systems. *Contrib. Mineral. Petrol.*, **40**, 259-274.

Duddy, I. R., P. F. Green, and G. M. Laslett, 1988: Thermal annealing of fission tracks in apatite 3. Variable temperature behaviour. *Chem. Geol. (Isot. Geosci. Sect.)*, **73**, 25-38.

Galbraith, R. F., 1981: On statistical models for fission track counts. *Mathematical Geology*, **13**, 471-478.

Gleadow, A. J. W., 1981: Fission track dating methods: What are the real alternatives? *Nucl. Tracks*, **5**, 3-14.

Gleadow, A. J. W., and I. R. Duddy, 1981: A natural long-term track annealing experiment for apatite. *Nucl. Tracks*, **5**, 169-174.

Green, P. F., 1981: A new look at statistics in fission track dating. *Nucl. Tracks*, **5**, 77-86.

Green, P. F., 1985: Comparison of zeta calibration baselines for fission track dating of apatite, zircon and sphene. *Chem. Geol.*, **58**, 1-22.

Green, P. F., 1986: On the thermo-tectonic evolution of Northern England: Evidence from fission track analysis. *Geol. Mag.*, **123**, 493-506.

Green, P. F., I. R. Duddy, G. M. Laslett, K. A. Hegarty, A. J. W. Gleadow, and J. F. Lovering, 1989a: Thermal annealing of fission tracks in apatites 4. Quantitative modelling techniques and extension to geological time scales. *Chem. Geol. (Isot. Geosci. Sect.)*, **79**, 155-182.

Green, P. F., I. R. Duddy, A. J. W. Gleadow, and J. F. Lovering, 1989b: Apatite fission track analysis as a paleotemperature indicator for hydrocarbon exploration, in Thermal history of sedimentary basins. In: N. D. Naeser, and T. H. McCulloch (Eds.), Springer-Verlag, New York.

Hodges, K. V., 1991: Pressure-Temperature-Time Paths. *Annual Reviews of Earth and Planet. Sci. Lett.*, **19**, 207-236.

Hurford, A. J., 1990: International union of geological sciences subcommission on geochronology: Recommendation for the standardization of fission track dating calibration and data reporting. *Nucl. Tracks*, **17**, 233-236.

Hurford, A. J., and P. F. Green, 1982: A users' guide to fission track dating calibration, Earth *and Planet. Sci. Lett.*, **59**, 343-354.

Hurford, A. J., and P. F. Green, 1983: The zeta age calibration of fission track dating. *Isot. Geosci*, **1**, 285-317.

Hurford, A, J., and R. T. Watkins, 1987: Fission track age of the tuffs of the Buluk Member, Bakate Formation, northern Kenya: A suitable fission track age standard. *Chem. Geol.,* **66**, 209-216.

Kamp, P. J. J., P. F. Green, and S. H. White. 1989: Fission track analysis reveals character of collisional tectonics in New Zealand. *Tectonics*, **8**, 169-195.

Kao, M.-H., 1998: Tectonic Evolution of the Marlborough Region, South Island, New Zealand, (Unpublished) Ph.D., University of Waikato, New Zealand.

Kao, M.-H., 2001: Thermo-tectonic history of the Marlborough Region, South Island, New Zealand. *TAO*, **12**, 31-50.

Laslett, G. M., P. F. Green, I. R. Duddy, and A. J. W. Gleadow, 1987: Thermal annealing of fission tracks in apatite, 2. A quantitative analysis. *Chem. Geol. (Isot. Geosci. Sect.),* **65**, 1-13.

Lensen, G. J., 1962: Sheet 16, Kaikoura (1st Edn). Geological Map of New Zealand 1:250, 000, Department of Scientific and Industrial Research, Wellington, New Zealand.

Naeser, C. W., 1979: Thermal history of sedimentary basins in fission track dating of subsurface rocks. *Spec. Publ. Soc. econ. Paleont. Miner.*, **26**, 109-112.

Reay, M. B., 1993: Geology of the Middle Clarence Valley, Institute of Geological and Nuclear Sciences geological map 10, 1 sheet + 144p, Institute of Geological and Nuclear Sciences Ltd., Lower Hutt, New Zealand.

Rohrman, M., P. van der Beek, P. nas Andriessen, 1994. Syn-rift thermal structure and post-rift evolution of the Oslo rift (southeast Norway): New Constraints from fission track thermochronology. *Earth and Plane. Sci. Lett.*, **127**, 39-54.

Suggate, R. P., 1978a: The Kaikoura Orogeny. In: Suggate, R. P., Stevens, G. R., Te Punga, M. T. (Eds.), 672-673, Chapter 10, The geology of New Zealand.

Suggate, R. P., 1978b: The Kaikoura Orogeny. In: Suggate, R. P., Stevens, G. R., Te Punga, M. T. (Eds.), 680-682, Chapter 10, The geology of New Zealand.

Tippett, J. M., and P. J. J. Kamp, 1993: Fission Track Analysis of the Late Cenozoic Vertical Kinematics of Continental Pacific Crust, South Island, New Zealand. *J. Geophys. Res.*, **98**, 16119-16148.