Tectonic interpretation in the Modi Khola valley, central Nepal using zirconium-in-rutile Thermometry

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1. Introduction

Metamorphism of the Greater and Lesser Himalayan rocks have been studied by Martin et al. (2010) and Corrie and Kohn (2011). Both groups in the Modi Khola valley, central Nepal and used similar thermobarometric methods. The two groups did not produce the same pressure/temperature estimates for the area of study, which has leads to inconsistencies in interpretations of faulting of the region. These discrepancies have implications for the tectonic interpretation of the region, using the zirconium-in-rutile thermometer calibrated by Tomkins et al. (2007). Furthermore, the temperature estimates calculated from this thermometer will be used as closure temperatures to compute the relative cooling rates of one side of the fault to the other. A sense of motion across the Bhanuwa fault can then be interpreted.

2. Geologic Setting

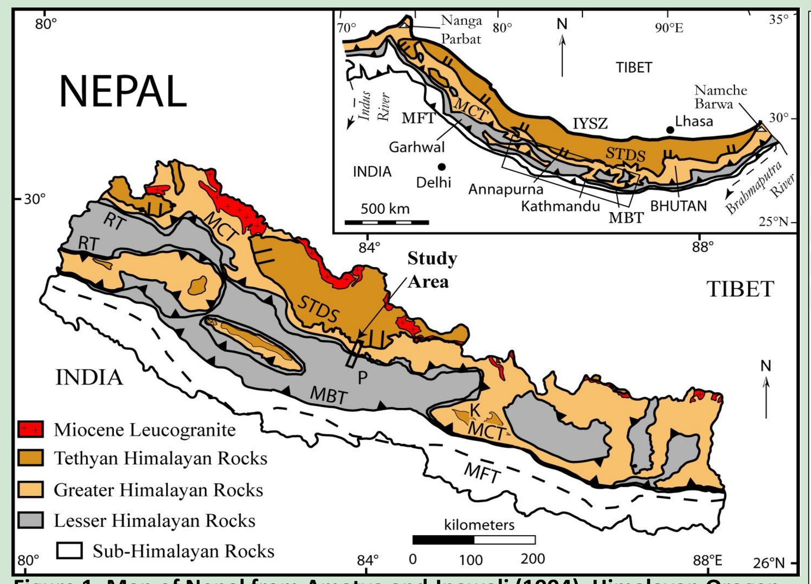


Figure 1: Map of Nepal from Amatya and Jnawali (1994). Himalayan Orogen inset from Sorkhabi and Macfarlane (1999)

- Major faults and rock units
- Main Frontal thrust, Main Boundary thrust, Main Central thrust, South Tibet detachment system
- Study area is in Greater Himalayan rocks

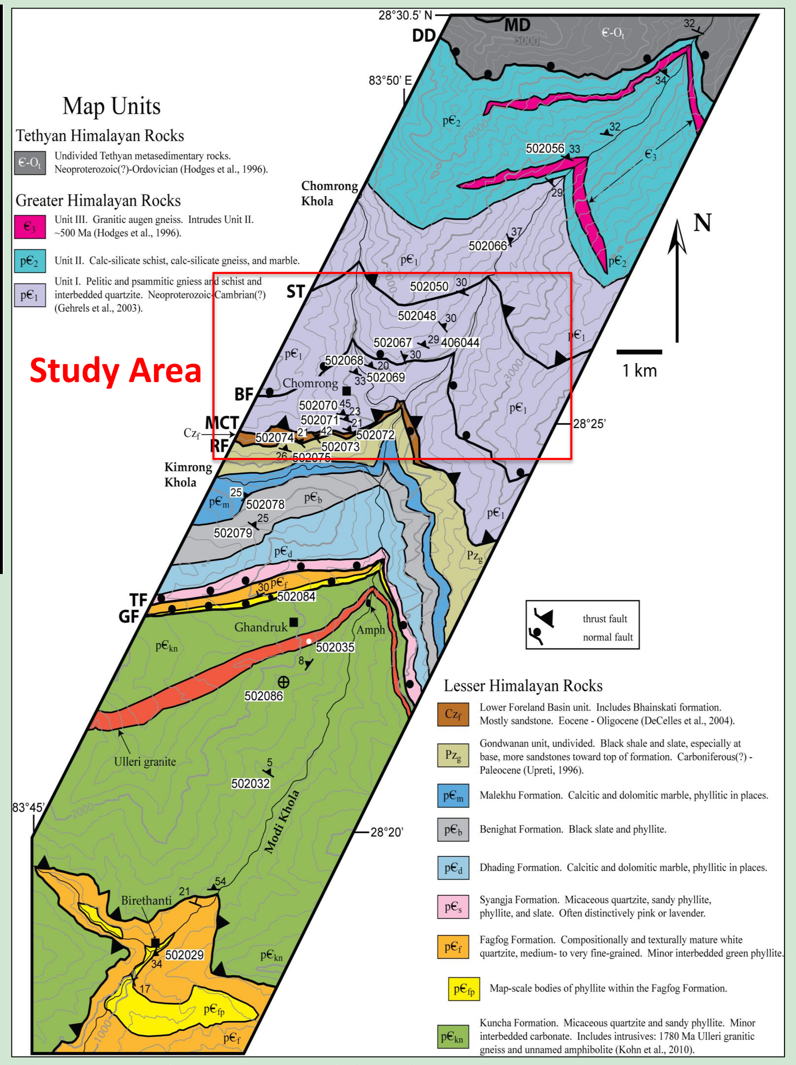


Figure 2: Map from Martin et al. (2010)

-Modi Khola valley, central Nepal
-Focusing on the Bhanuwa fault
-Part of Unit 1 Greater Himalayan rocks
-Metamorphosed muddy sandstones
-Martin et al. samples collected at strike and dip symbols

3. Background

Martin et al. (2010) overview
-thermometer: garnet-biotite
-barometer: garnet-muscovite-quartz-biotite-plagioclase
-4 kbar pressure difference led to interpretation of normal fault

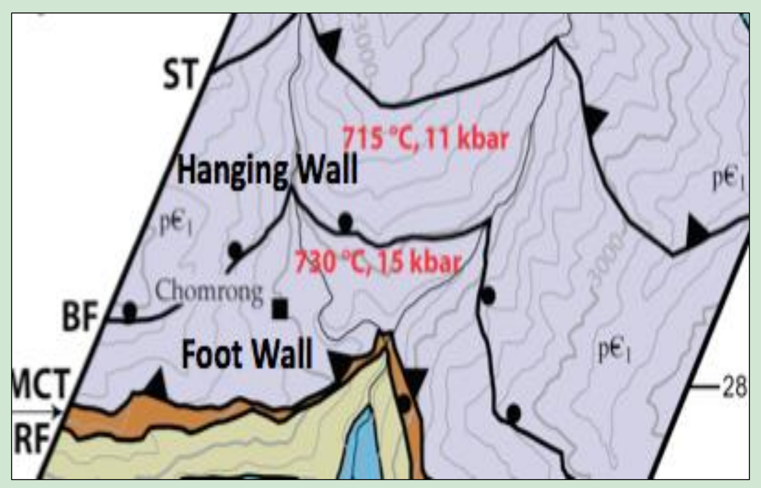


Figure 3: Map from Martin et al (2010). Zoomed in on the Bhanuwa Fault with pressure and Temperature estimates from Martin et al. (2010)

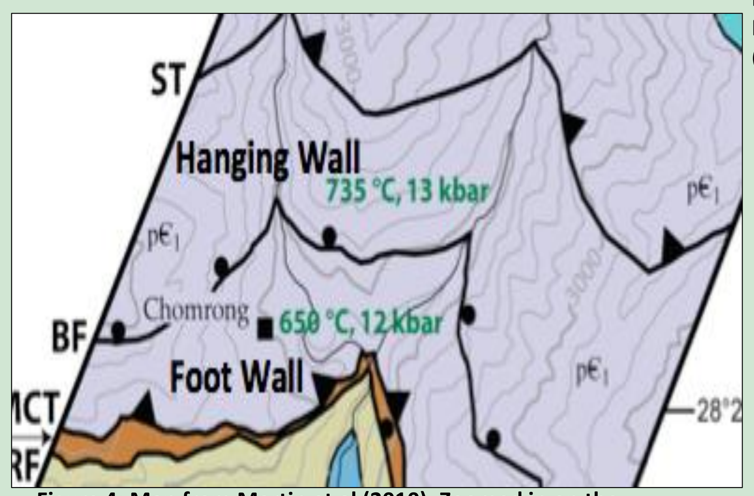
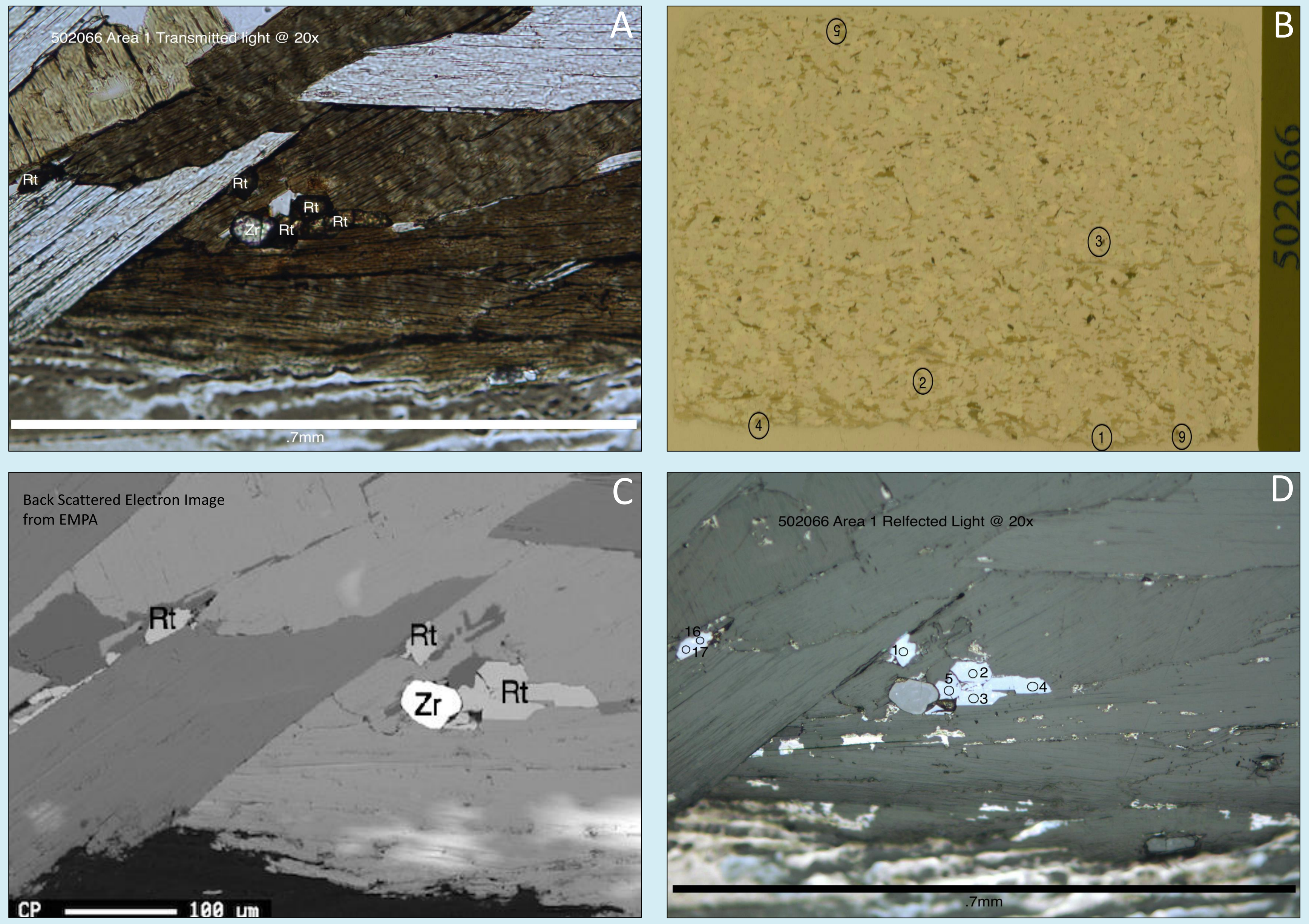


Figure 4: Map from Martin et al (2010). Zoomed in on the Bhanuwa Fault with pressure and Temperature estimates from Corrie and Kohm (2011)

Corrie and Kohn (2011) overview
-thermometer: garnet-biotite
-barometer: garnet-muscovite-quartz-biotite-plagioclase
-85°C temperature difference led to interpretation of thrust fault

4. Hypothesis

Zirconium-in-rutile temperature estimates are consistent within uncertainty with estimates from Martin et al. (2010) and Corrie and Kohn (2011)



5. Methods

A. Analyze thin sections using petrographic microscope. Document the mineral assemblages found and locate rutile grains using petrographic/optical properties for further analysis using the EPMA. (Photo A above)
B. Record location of rutile grains on thin section map (Photo B above)
C. Using the EPMA locate rutile grains (Photo C above)
D. Choose spots for analysis on grains of rutile to be measured for their zirconium concentrations (Photo D above)
E. Plug in the concentrations of zirconium in ppm into the Tomkins et al. (2007) α-quartz calibration of the zirconium-in-rutile thermometer (Formula E)
F. Use estimated closure temperatures calculated and equation 23 from Dodson (1972) to calculate cooling rates (Formula F)

6. Equations

$$T(°C) = \frac{83.9 + 0.410P}{0.1428 - R\ln\phi} - 273 \quad \text{E}$$

P is pressure in kbar,
R is the gas constant (.0083144 kJ/K)
Φ is the Zr concentration in ppm.
Pressures estimated across the fault from Martin et al. (2010) and Corrie and Kohn (2011) will be used.

$$\frac{E}{RT_c} = \ln(-(ART_c^{\,2} D_0)/(Ea^2\left(\frac{dT}{dt}\right))) \quad \text{F}$$

E is the activation energy
R is the gas constant
T_c is the closure temperature
A is the geometric factor ($A=e^G$)
D_0 is the pre-exponential factor in the Arrhenian expression of diffusion coefficient
a is the radius of the grain
(dT/dt) is the cooling rate.

Using values from Cherniak et al. (2007) for E and D_0, values given at 170±30 kJ/mol for E and $9.8E^{-11}$ cm^2/s for D_0. It was concluded by Blackburn et al. (2012) that 200kJ/mol is more appropriate value for D_0. T_c and a are my estimated values and radius determined from photomicrograph images, the G for sphere given as 4.0066 from Ganguly et al. (2009).

7. Uncertainty

Uncertainties on the EPMA can be estimated using standard counting statistical techniques. These uncertainties are estimated from a modified version of the equation *2σ=2((√N)/N)*100%*. Where N is the number of counts at peak position.
An example given below has an uncertainty of 15% due to counting statistics and a pressure of 12 kbars. This example is measured as 120±36 ppm Zr, which gives a temperature range of 565-608°C.

Zr (ppm)	2σ	Low Temp.	High Temp.
120	36	565	608

Calculated values of cooling rate only show minimal uncertainty, that of the analytical uncertainties from the EPMA. Other uncertainties affect the true absolute value of the cooling rate, but for the purposes of this study in terms of relative cooling rates of hanging wall to footwall those uncertainties cancel out. The uncertainty of grain size, more importantly its radius, needs to be looked at further since it does not cancel out along with the uncertainties from standard counting statistical techniques

8. Results

					MARTIN			CORRIE+KOHN		
spot	wt%	ppm zro2	ppm zr	2σ	-2σ		+2σ	-2σ		+2σ
1	0.0174	174	129	38	567	590	609	575	598	617
2	0.0158	158	117	38	558	584	603	565	592	611
3	0.0171	171	127	37	565	589	607	573	597	616
4	0.0174	174	129	38	567	590	609	575	598	617
5	0.0245	245	181	38	598	615	629	606	623	638
6	0.0130	130	96	38	538	570	593	546	578	601
7	0.0128	128	95	37	537	569	592	545	577	600
8	0.0131	131	97	38	539	571	593	547	579	601
9	0.0135	135	100	38	542	573	595	550	581	603
10	0.0118	118	87	37	529	564	588	536	572	596
16	0.0188	188	139	38	574	596	613	582	604	621
17	0.0154	154	114	38	555	582	602	563	590	610
18	0.0191	191	141	38	575	597	614	583	605	622
19	0.0214	214	158	38	586	605	621	594	613	629
11	0.0194	194	144	38	592	614	632	581	602	619
12	0.0307	307	227	38	635	649	661	622	636	648
13	0.0178	178	132	38	585	608	626	573	596	614
14	0.0160	160	118	38	574	600	620	563	588	608
15	0.0154	154	114	38	570	598	618	559	586	606
20	0.0424	424	314	38	664	675	685	651	662	672
21	0.0380	380	281	39	654	666	676	641	653	663
22	0.0407	407	301	39	660	672	682	648	659	668
23	0.0425	425	315	39	664	675	685	652	662	672
24	0.0411	411	304	39	661	672	682	648	659	669
25	0.0421	421	312	39	663	674	684	651	661	671
26	0.0432	432	320	39	666	676	686	653	663	673

Table 1: Temperature estimates for hanging wall sample 502066(Yellow) and footwall sample 502069(Red). Columns under MARTIN used pressure from Martin et al. (2010). Columns under CORRIE+KOHN used pressures from Corrie and Kohn (2011)

		MARTIN			CORRIE	+ KOHN	
spot	radius (cm)	temp (K)	Cooling rate (°C/M.y)	±2σ	temp (K)	Cooling rate (°C/M.y)	±2σ
1	0.0014	855.47	1.56	1.36	863.48	2.07	1.78
2	0.0012	848.83	1.84	1.80	856.77	2.44	2.36
3	0.0009	854.27	3.70	3.24	862.26	4.89	4.24
4	0.0010	855.47	3.36	2.93	863.48	4.44	3.82
5	0.0012	879.92	5.39	3.21	888.15	7.08	4.17
6	0.0006	835.70	3.71	4.59	843.52	4.93	6.04
7	0.0009	834.67	1.82	2.28	842.48	2.42	3.00
8	0.0014	836.21	0.78	0.96	844.03	1.04	1.26
9	0.0014	838.21	0.84	1.00	846.05	1.12	1.31
10	0.0014	829.33	0.60	0.84	837.09	0.81	1.11
16	0.0010	860.88	3.57	2.85	868.94	4.71	3.72
17	0.0010	847.08	2.19	2.20	855.01	2.90	2.89
18	0.0009	862.00	4.84	3.83	870.06	6.39	4.99
19	0.0010	870.09	4.90	3.39	878.23	6.45	4.41
11	0.0020	879.25	1.79	1.37	867.14	1.19	0.92
12	0.0030	913.60	2.41	1.10	901.01	1.62	0.75
13	0.0012	873.10	4.29	3.54	861.07	2.84	2.39
14	0.0012	865.59	3.32	3.12	853.66	2.19	2.10
15	0.0012	862.93	3.03	3.01	851.04	1.99	2.02
20	0.0018	939.41	14.34	4.62	926.46	9.75	3.19
21	0.0017	930.49	12.77	4.64	917.67	8.65	3.19
22	0.0017	936.06	15.07	5.08	923.16	10.23	3.50
23	0.0022	939.60	9.78	3.16	926.65	6.65	2.18
24	0.0022	936.86	9.02	3.05	923.95	6.13	2.10
25	0.0022	938.83	9.56	3.14	925.89	6.50	2.17
26	0.0019	940.95	13.07	4.17	927.98	8.89	2.88

Table 2: Cooling rate estimates for hanging wall sample 502066(Yellow) and footwall sample 502069(Red). Columns under MARTIN used temperatures estimates from Martin et al. (2010) pressures. Columns under CORRIE+KOHN used temperature estimates from Corrie and Kohn (2011) pressures

9. Conclusions

1. After calculating temperature estimates using the zirconium-in-rutile thermometer it was noticed that these temperatures are lower than other works. We concluded that these rutile grains are too small to record peak temperatures.
2. Interpreting the temperature estimates as closure temperatures, they could be plugged into an equation to get cooling rate. The absolute values of the cooling rates are not important, what matters is the relative cooling rates of one side of the fault to the other side. Assume that the faster cooling rate= faster exhumation rate and that the transformation from cooling rate to exhumation rate was the same for both the hanging wall and footwall. If the hanging wall exhumed more slowly than the footwall it was a normal fault. If the hanging wall exhumed more rapidly, then it was a thrust.
3. Initial results based on a very small data set are consistent with the samples in the footwall samples cooling quicker than the hanging wall samples, suggesting normal fault. This conclusion will be explored further next semester.

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