

# **A different take on fission-track annealing in apatite**

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## **Table supplements**

**Table T1.** Model-1 and model-2 fits to the isochronal annealing data of Carlson et al. (1999; BC-99), Barbarand et al. (2003; JB-03), and Ravenhurst et al. (2003; CR-03).

Source	$t$ (h)	$\ln(t(s))$	$N$	$A_1$	$B_1$	$C_1$	$R$	$MSQR$	$A_2$	$B_2$	$R$	$MSR$
BC-99	1	8.19	64	-0.6925	1.0579	1.4007	0.982	0.0896	-1.0062	1.3588	0.981	0.0937
	2	8.88	12	-0.2786	0.4974	1.5688	0.918	0.0054	-0.4572	1.0484	0.917	0.0049
	10	10.5	51	-1.1199	1.5140	1.4328	0.991	0.0324	-1.0384	1.4406	0.991	0.0321
	100	12.8	99	-0.9237	1.4750	1.4934	0.983	0.0554	-0.9387	1.4912	0.983	0.0549
	1000	15.1	40	-1.4796	2.2486	1.4825	0.992	0.0526	-0.8887	1.5605	0.988	0.0762
JB-03	10	10.5	58	-0.8466	1.3052	1.4389	0.959	0.2642	-1.0122	1.4255	0.959	0.2608
	100	12.8	26	-0.5319	1.0467	1.5695	0.977	0.0996	-1.1283	1.5084	0.975	0.1050
	1000	15.1	29	-0.4761	1.1013	1.6149	0.955	0.1689	-1.0022	1.5513	0.953	0.1681
CR-03	0.30	6.98	28	-0.6934	0.9770	1.3344	0.991	0.0534	-1.0149	1.2885	0.990	0.0612
	2.25	9.00	27	-0.4513	0.8034	1.4235	0.992	0.0506	-1.0192	1.3443	0.987	0.0847
	23.0	11.3	19	-1.3035	2.3068	1.1621	0.969	0.0458	-0.7517	1.3592	0.965	0.0495
	167	13.3	21	-0.1896	0.6379	1.6183	0.994	0.0476	-1.0281	1.4859	0.978	0.1681
	1488	15.5	11	-0.5806	0.9869	1.6394	0.996	0.0198	-1.0326	1.5384	0.992	0.0333
	5723	16.8	4	-20.083	569.01	-24.957	0.968	0.0050	-0.9391	1.6353	0.968	0.0025

$A_1, B_1, C_1$ : Model-1 parameters (equation 1);  $A_2, B_2$ : Model-2 parameters (equation 2);  $t$ : annealing time;  $N$ : number of samples;  $R$ : correlation coefficient;  $MSR$ : mean squared residual.

**Table T2.** Model-2 parameter dependencies on annealing time for the combined data of Carlson et al. (1999), Barbarand et al. (2003) and Ravenhurst et al. (2003).

Model 2		Parameter	$U$	$V$	$R$	$MSR$
$S(\mu\text{m}) = A + \frac{B}{\frac{1000}{T(\text{K})} - B}$	REG	$A$	0.00415	-1.03501	0.10286	0.00803
		$B$	0.03190	1.07298	0.95265	0.00093
$A = U_A \ln(t(\text{s})) + V_A$	MSR	$A$	0.00270	-1.00800		
		$B$	0.03140	1.08500		0.13669
$B = U_B \ln(t(\text{s})) + V_B$	CON	$A$	<b>0.00000</b>	<b>-0.99000</b>		
		$B$	<b>0.03160</b>	<b>1.08500</b>		0.13704

REG: ( $U, V$ )-parameter estimates of the linear dependence of  $A$  and  $B$  on  $\ln(t)$  based on the regression (Figure 2e,f); MSR: estimates based on lowest mean squared residual; CON: including the constraint  $U_A = 0$  (Figure 3).  $U$ : slope;  $V$ : intercept;  $R$ : correlation coefficient;  $MSR$ : mean squared residual.

**Table T3.** Overview of regression lines fitted to the data trends in Figures 2, 5 and 6. (1-3): relationships between the reduced track densities and the reduced track lengths based on the data of Green (1988) for the Renfrew, Durango and Strontian apatites; (4-5) relationships between the annealing rates of induced fission tracks in the Renfrew and Durango apatites and those in the Bamble apatite; (6-9): linear trends fitted to the track shortening vs. time fitted to the ambient-temperature annealing data of Tamer and Ketcham (2020) for the Durango, Fish Canyon, Tioga and Renfrew apatites (excluding data from other studies).

Nr.	Apatite	Interval	Equation	R	Fig.
1	Renfrew	$0 \leq \left[ \frac{L}{L_0} \right]_F \leq 0.720$	$\left[ \frac{\rho}{\rho_0} \right]_F = 3.297 \left[ \frac{L}{L_0} \right]_F - 1.653$	0.985	S2
		$0.720 \leq \left[ \frac{L}{L_0} \right]_F \leq 1$	$\left[ \frac{\rho}{\rho_0} \right]_F = \left[ \frac{L}{L_0} \right]_F$		
2	Durango	$0 \leq \left[ \frac{L}{L_0} \right]_D \leq 0.647$	$\left[ \frac{\rho}{\rho_0} \right]_D = 3.112 \left[ \frac{L}{L_0} \right]_D - 1.366$	0.982	S2
		$0.647 \leq \left[ \frac{L}{L_0} \right]_D \leq 1$	$\left[ \frac{\rho}{\rho_0} \right]_D = \left[ \frac{L}{L_0} \right]_D$		
3	Strontian	$0 \leq \left[ \frac{L}{L_0} \right]_S \leq 0.539$	$\left[ \frac{\rho}{\rho_0} \right]_S = 3.566 \left[ \frac{L}{L_0} \right]_S - 1.382$		S2
		$0.539 \leq \left[ \frac{L}{L_0} \right]_S \leq 1$	$\left[ \frac{\rho}{\rho_0} \right]_S = \left[ \frac{L}{L_0} \right]_S$		
4	Renfrew	$S \leq 2.094$	$S_F = 1.116 S - 0.045$	0.969	6
		$2.094 \leq S$	$S_F = 2.512 S - 2.968$	0.984	6
5	Durango	$S \leq 3.230$	$S_D = 1.061 S - 0.172$	0.982	
		$3.230 \leq S$	$S_D = 2.559 S - 5.010$	0.985	
6	Durango	-	$S_D = 0.029 \ln(t) - 0.070$	0.957	7
7	Fish Canyon	-	$S_C = 0.050 \ln(t) - 0.104$	0.956	7
8	Tioga	-	$S_T = 0.063 \ln(t) - 0.194$	0.984	7
9	Renfrew	-	$S_F = 0.077 \ln(t) - 0.348$	0.963	7

*R*: correlation coefficient; *L*: mean confined track length; *L*<sub>0</sub>: unannealed mean length;  $\rho$ : track density;  $\rho_0$ : unannealed track density; *S*: track length reduction in fluorapatite (*S<sub>F</sub>*), Durango (*S<sub>D</sub>*), Fish Canyon Tuff (*S<sub>C</sub>*), and Tioga apatite (*S<sub>T</sub>*).

**Table T4.** Equations used for forward modelling of the KTB age and mean length vs. depth profiles, in conjunction with the annealing model 2 (equation 2) and parameters in Supplement Table T2. See Supplement Figure S3 for eq. (3).

Nr.		Equation	R	Fig.	
1	F apatite	$L_0 = 15.63 + 0.283 Dpar$	$Dpar = 1.65 \rightarrow L_0 \approx 16.0$	0.904	-
2	F apatite	$\sigma_L = 0.0286 L^2 - 0.873 L + 7.464$		0.914	-
3	F apatite	$\left[\frac{\rho}{\rho_0}\right]_F = 2.355 \left[\frac{L}{L_0}\right]_F - 1.177$	$0 \leq \left[\frac{\rho}{\rho_0}\right]_F \leq 0.868$		S4
		$\left[\frac{\rho}{\rho_0}\right]_F = \left[\frac{L}{L_0}\right]_F$	$0.868 \leq \left[\frac{\rho}{\rho_0}\right]_F \leq 1$		

$L$ : mean confined-track length;  $L_0$ : mean initial length (Carlson et al., 1999);  $Dpar$ : size of track opening parallel to the  $c$ -axis (Donelick, 1991);  $\sigma_L$ : standard deviation of the track length distributions (Donelick et al., 1999);  $\rho$ : track density;  $\rho_0$ : unannealed track density.

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## Figure supplements

**Figure S1.** Mean lengths of unannealed and part-annealed induced tracks, plotted against  $D_{par}$ : (a) Carlson et al. (1999; 5.5 M HNO<sub>3</sub>, 20 s, 21 °C); (b) Barbarand et al. (2003; 5.0 M HNO<sub>3</sub>, 20 s, 20 °C); (c) Ravenhurst et al. (2003; 5.0 M HNO<sub>3</sub>, 11-47 s; 21 °C;  $D_{par}$  values are from Carlson et al., 1999). Grey symbols for gradual length reduction; green symbols for accelerated length reduction. Dotted line: unannealed induced tracks; dashed lines are parallel lines for part-annealed samples.

**Figure S2.** Reduced mean lengths ( $L/L_0$ ) of confined induced tracks in different apatites, plotted against the normalized track densities ( $\rho/\rho_0$ ) (data from Green, 1988). The 1:1-line represents gradual stage (open symbols). Dashed lines are regression lines to data for accelerated length reduction (shaded symbols); the line for the Renfrew data intersects the 1:1-line at  $L/L_0 = 0.72$  (dashed); the corresponding intersections are at  $L/L_0 = 0.64$  for Durango and  $L/L_0 = 0.54$  for Strontian apatite.

**Figure S3.** Decrease ( $S$ ;  $\mu\text{m}$ ) of the mean lengths of confined fission tracks due to isochronal annealing, plotted against the reciprocal temperature ( $1000 T(\text{K})^{-1}$ ); (a) data from Carlson et al. (1999; 5.5 M HNO<sub>3</sub>, 20 s, 21 °C); (b) data from Barbarand et al. (2003; 5.0 M HNO<sub>3</sub>, 20 s, 20 °C); (c) data from Ravenhurst et al. (2003; 5.0 M HNO<sub>3</sub>, 11-47 s; 21 °C). Annealing models for gradual length reduction fitted to data shown in grey; the data in green are excluded for reason of suspected accelerated length reduction. Solid line: model 1 (equation 1); dashed line: model 2 (equation 2).

**Figure S4.** Association between the reduced mean confined track lengths and normalized track densities in Renfrew apatite (Green, 1988), compared with our fit to the Carlson et al. (1999) data in Figure 8.

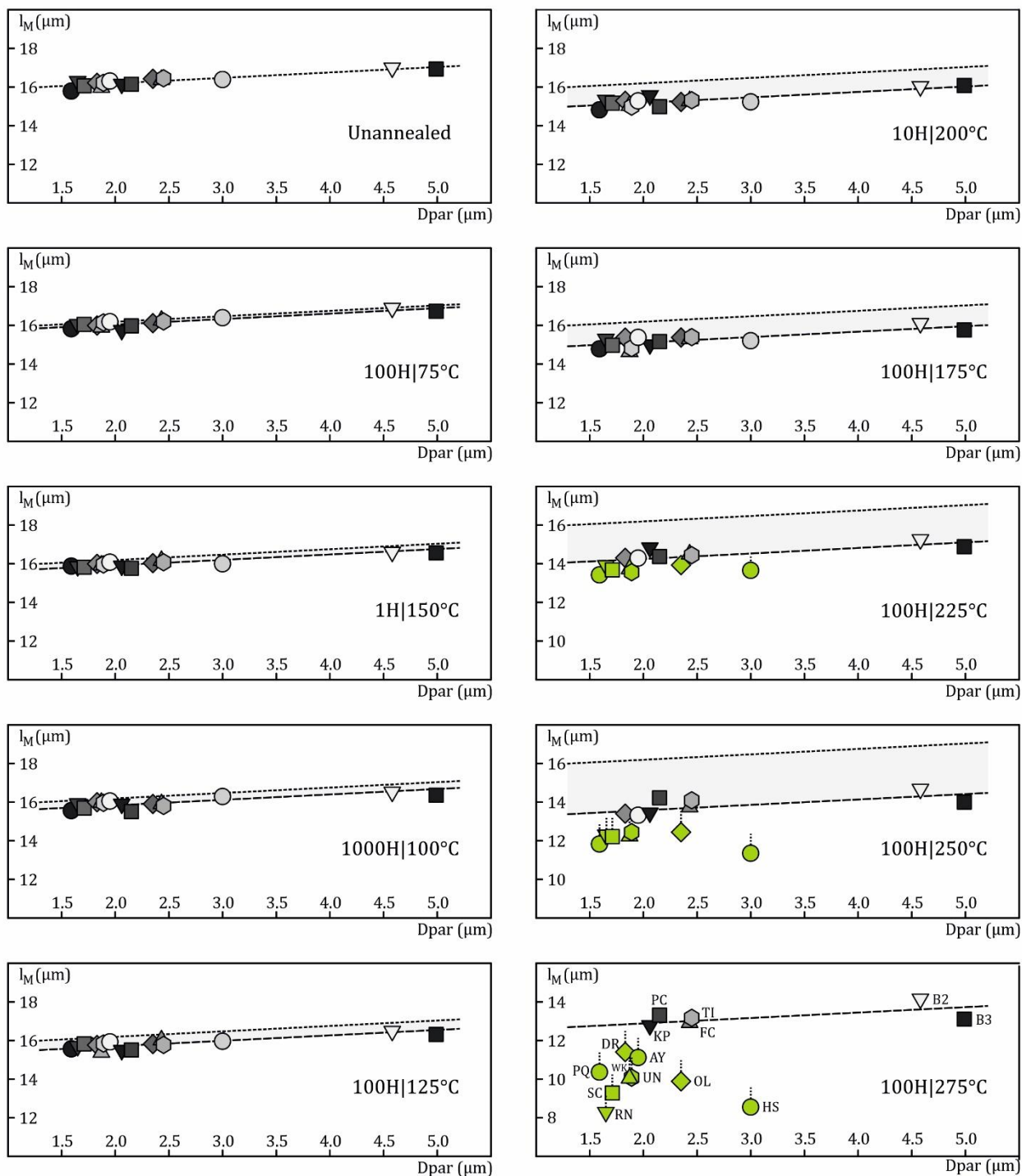


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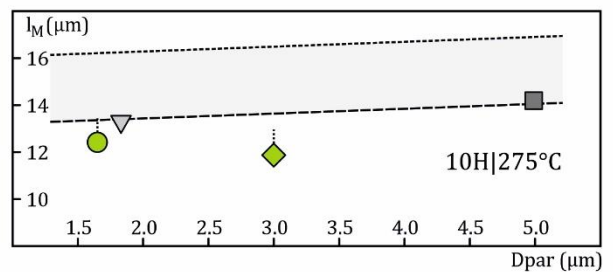
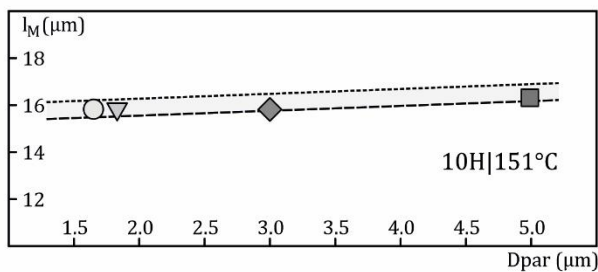
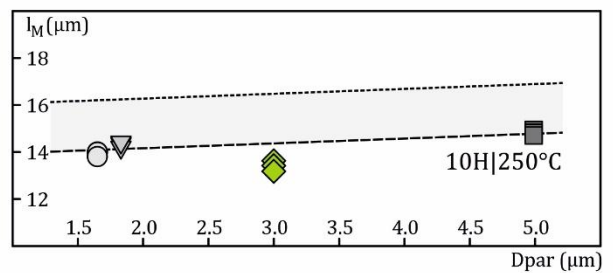
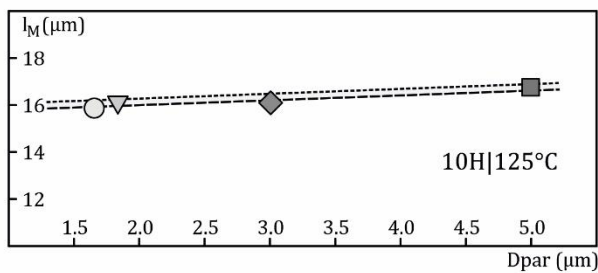
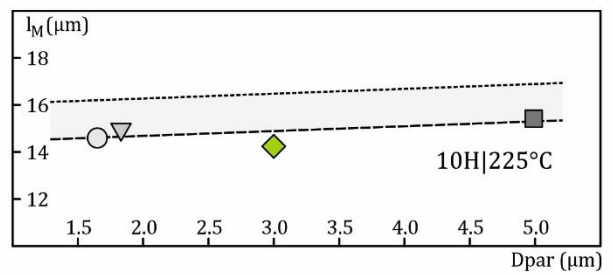
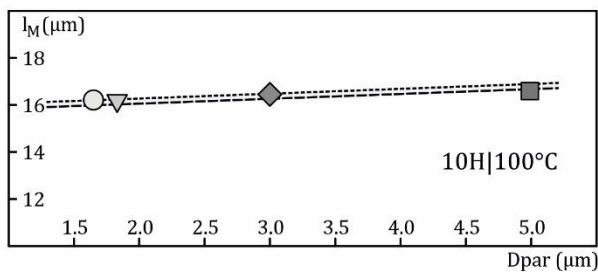
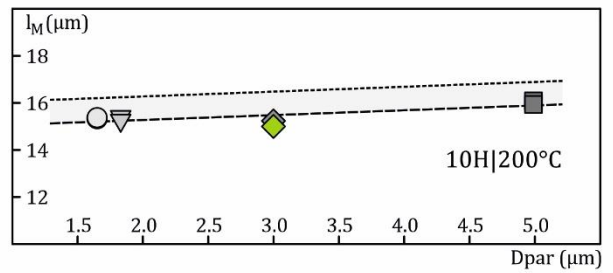
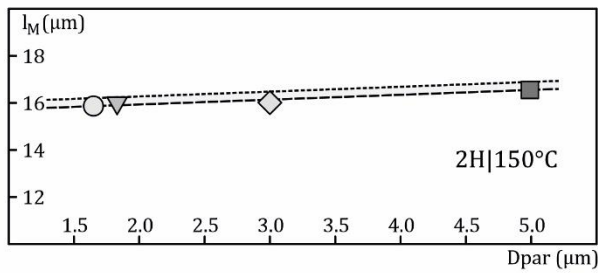
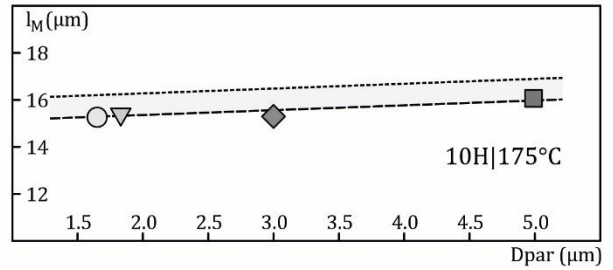
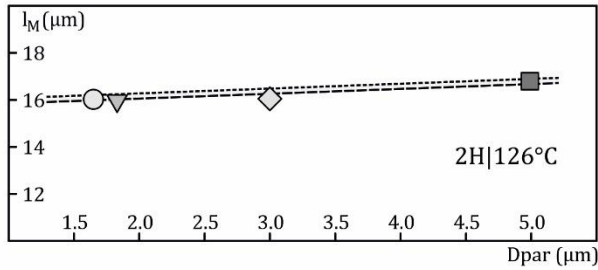


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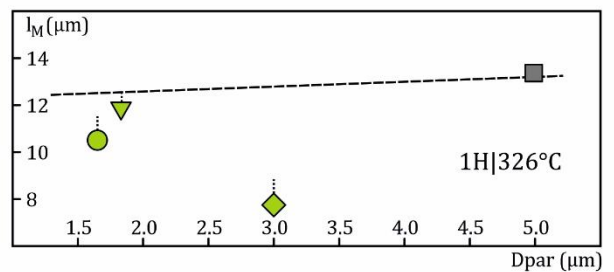
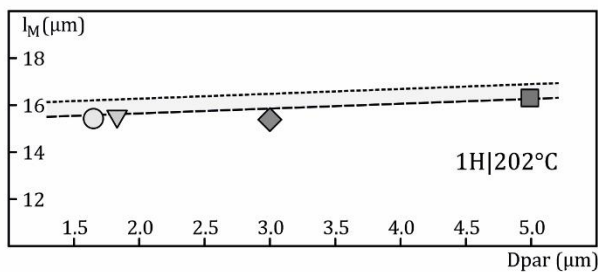
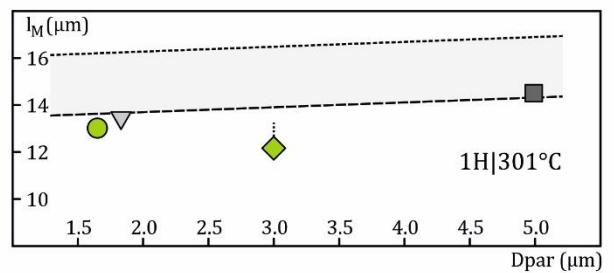
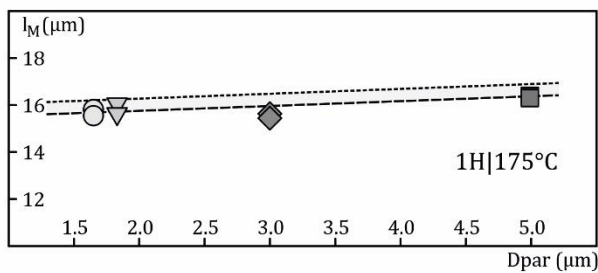
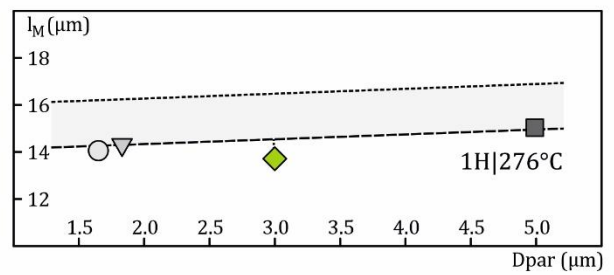
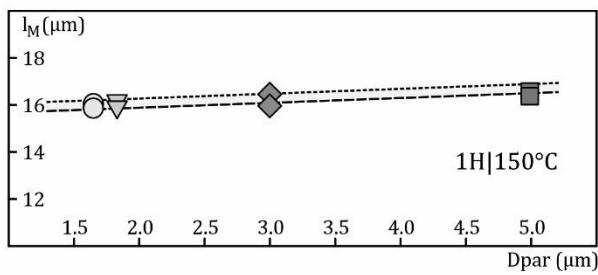
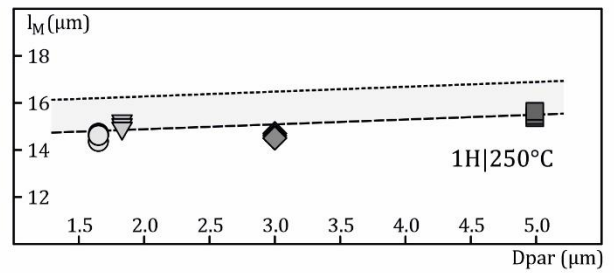
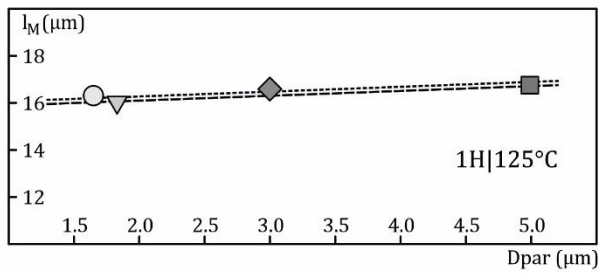
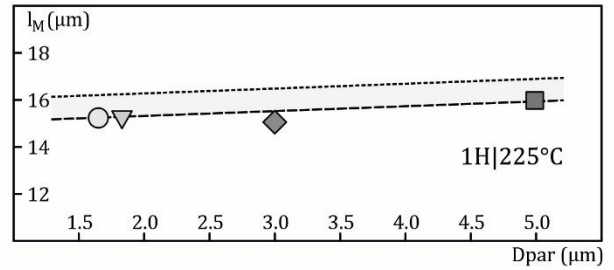
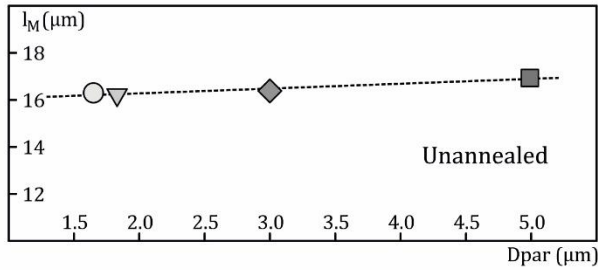


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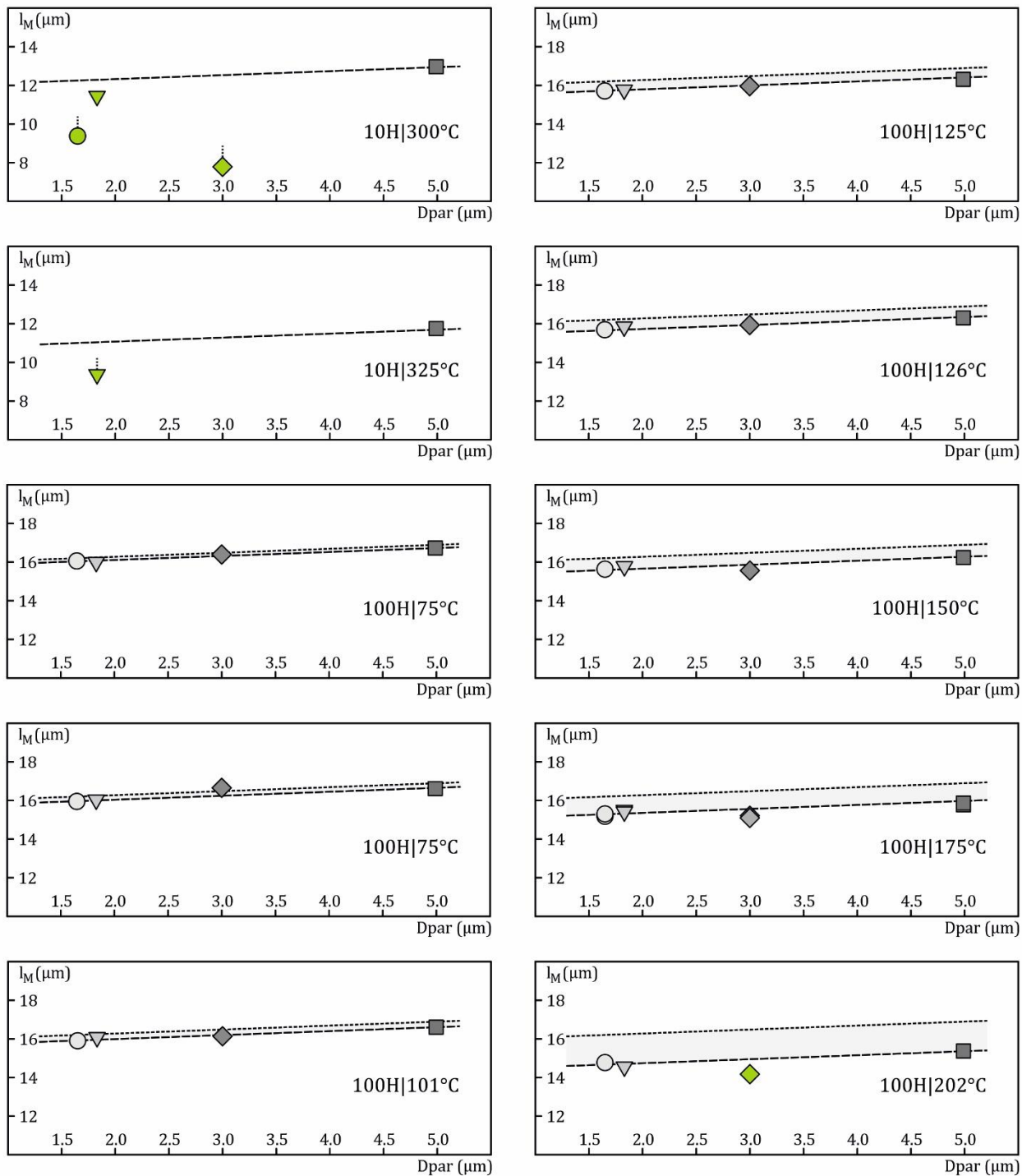


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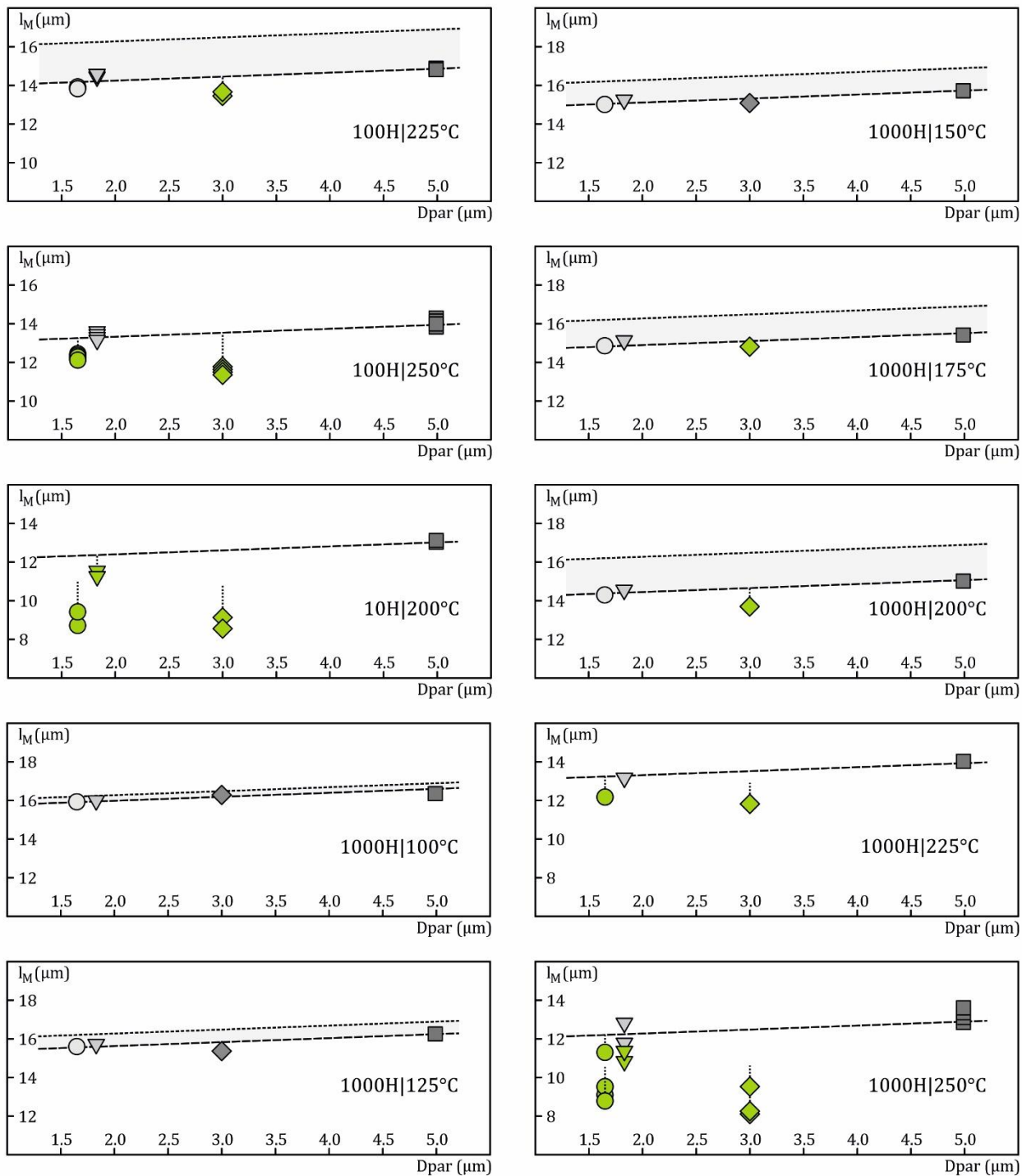
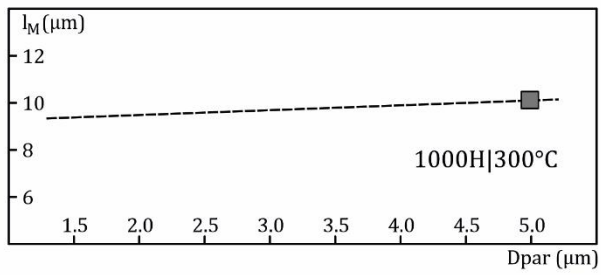
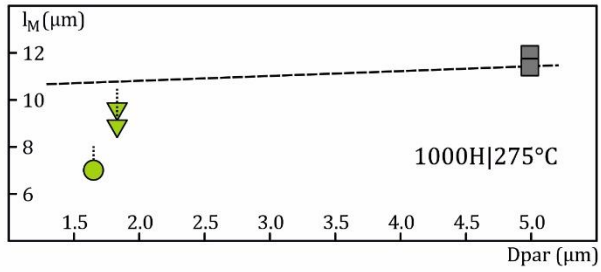


Figure S1(a)



**Figure S1(a)**

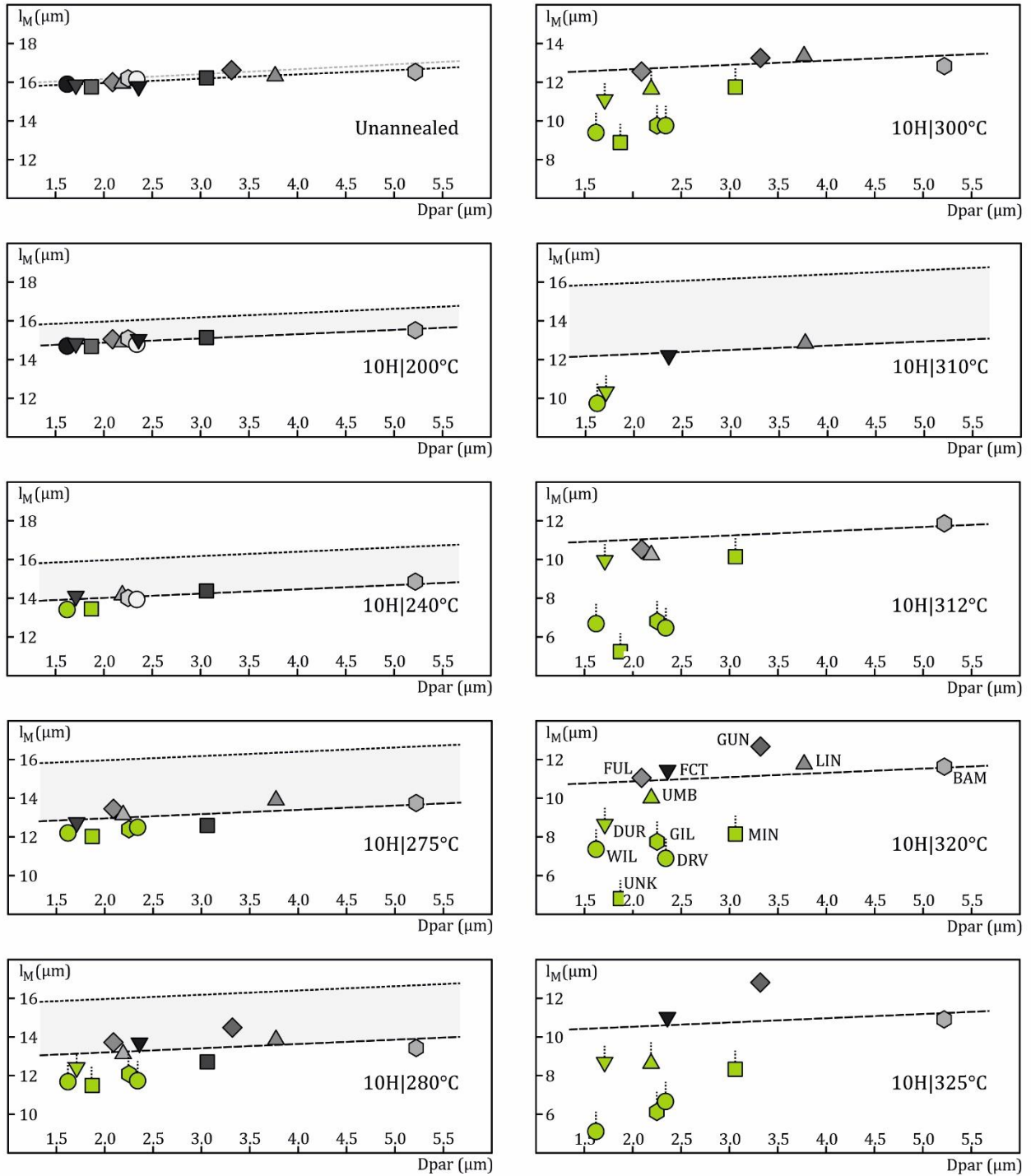


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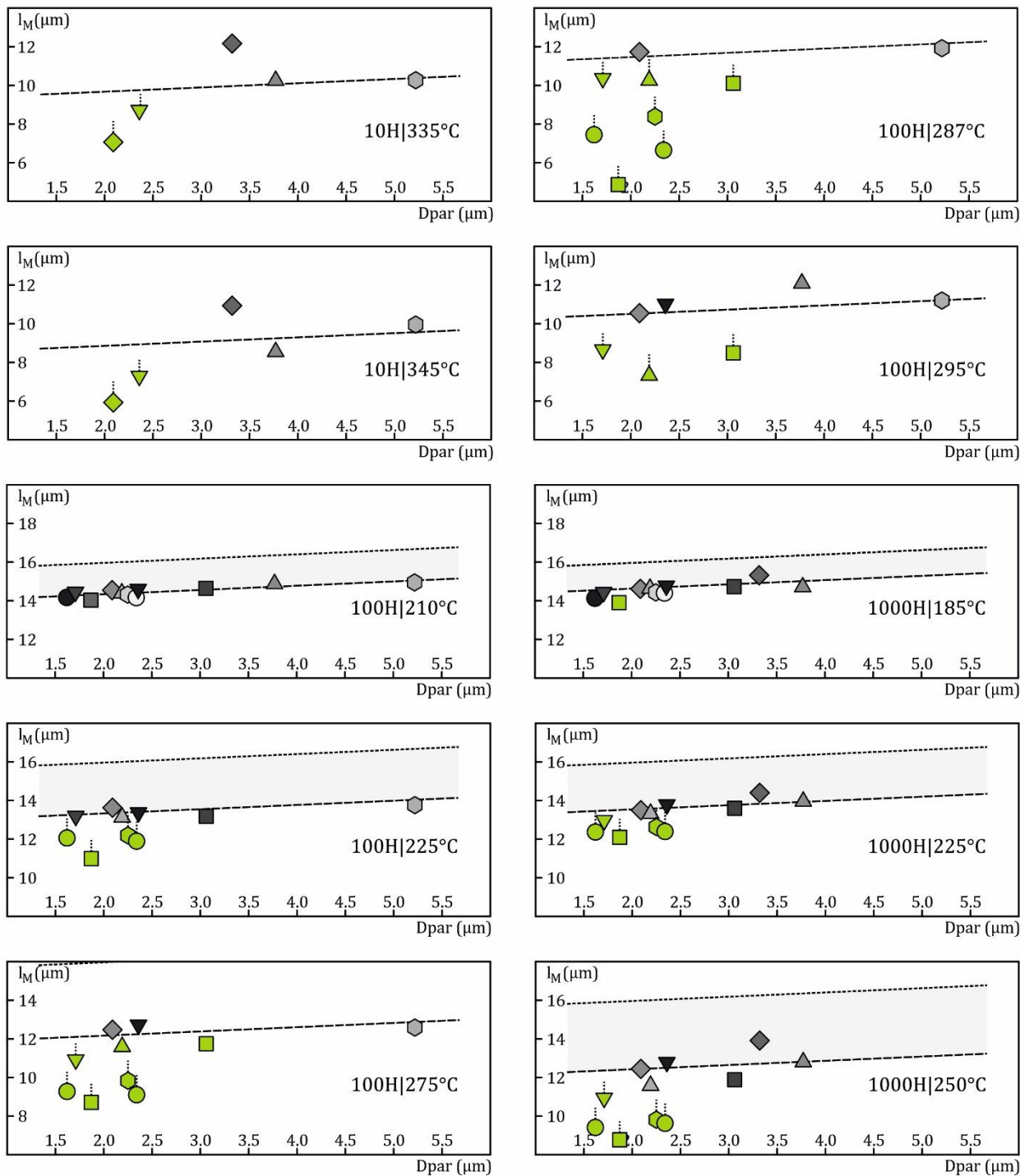


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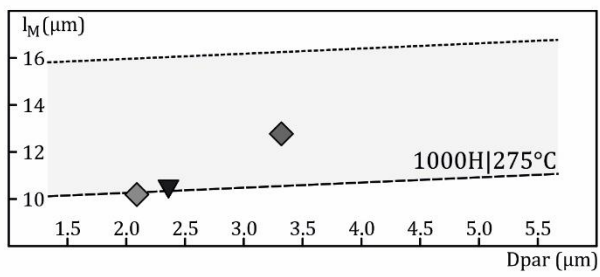
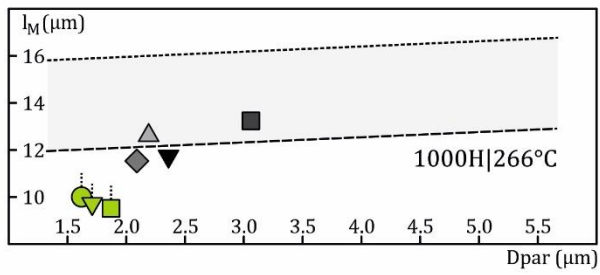
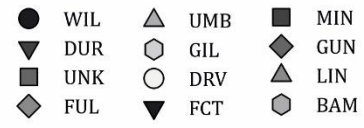
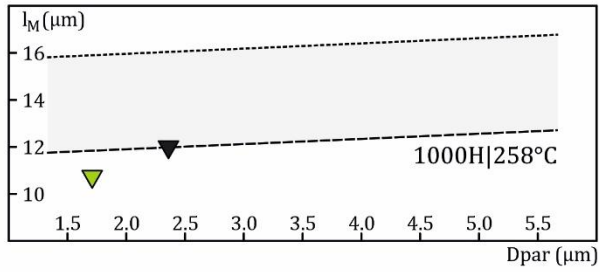


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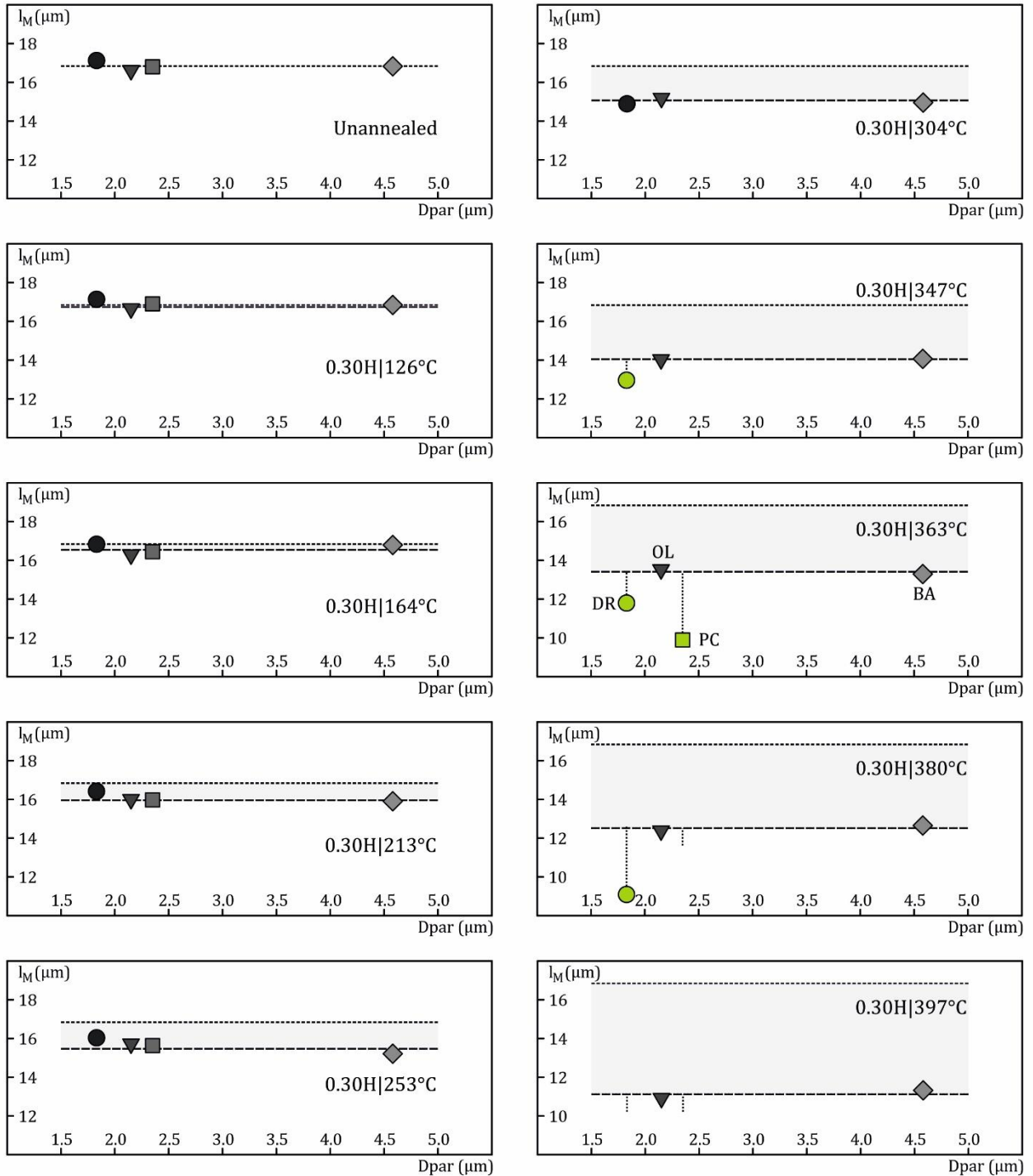


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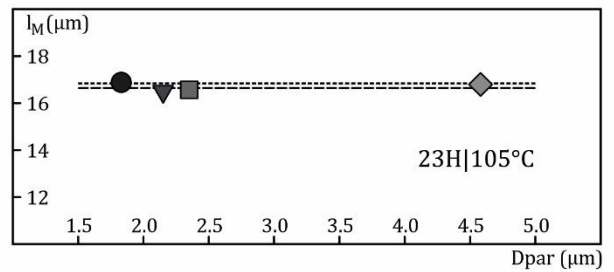
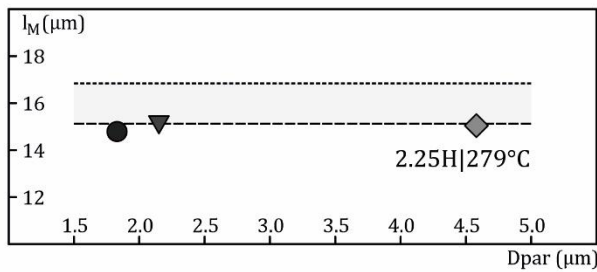
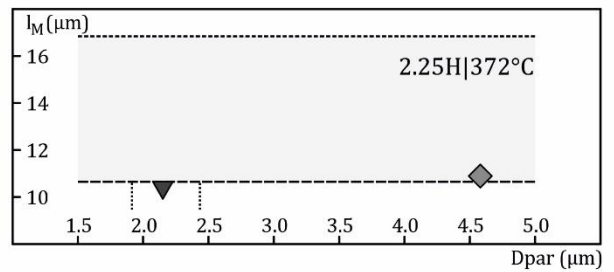
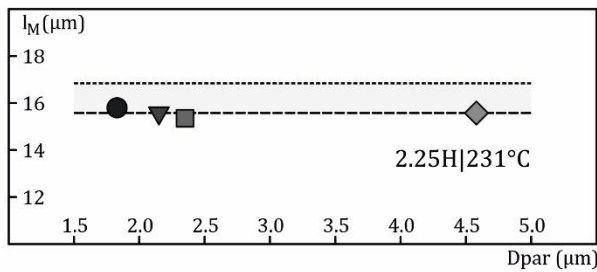
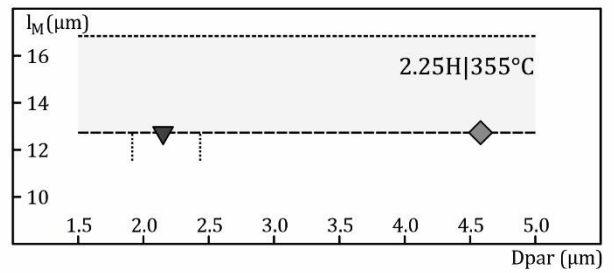
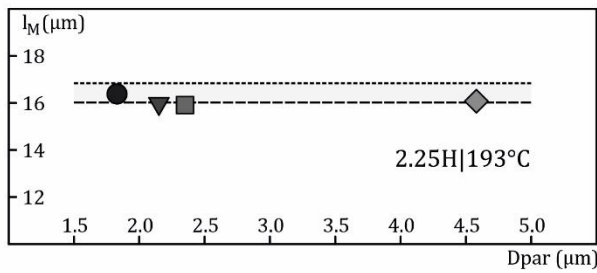
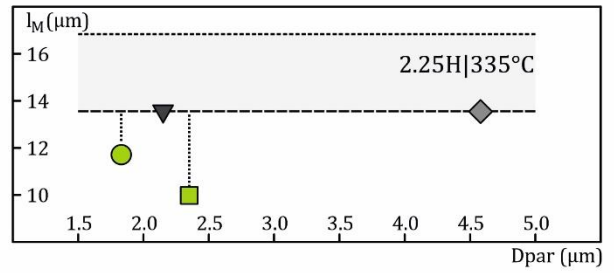
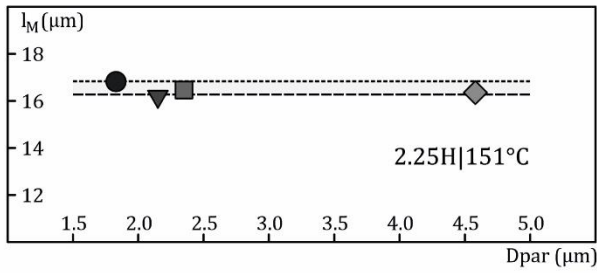
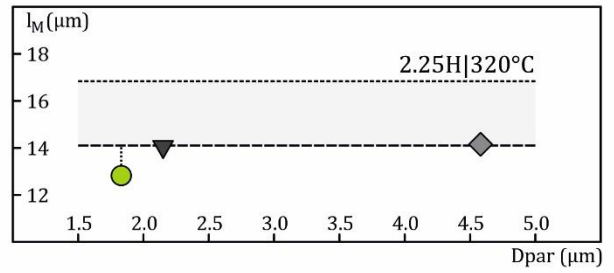
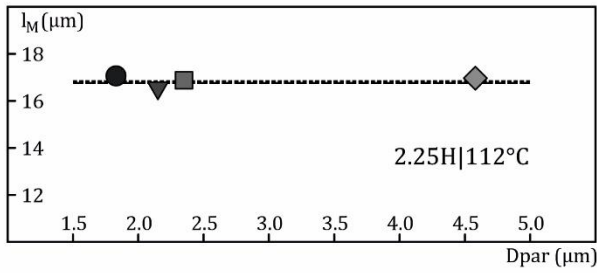


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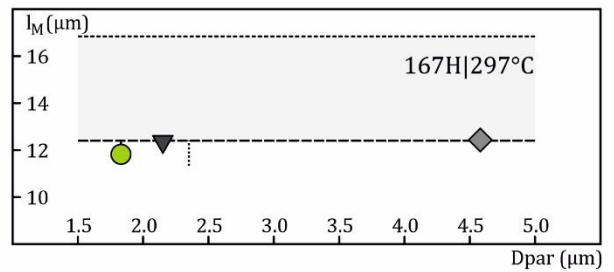
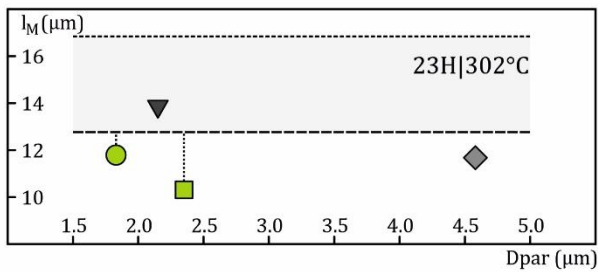
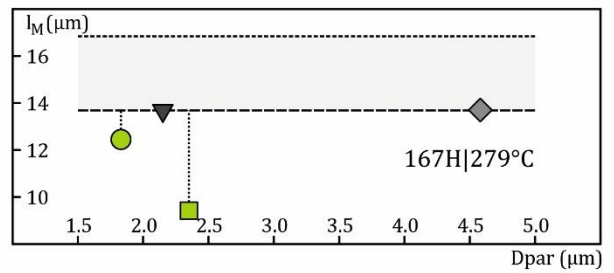
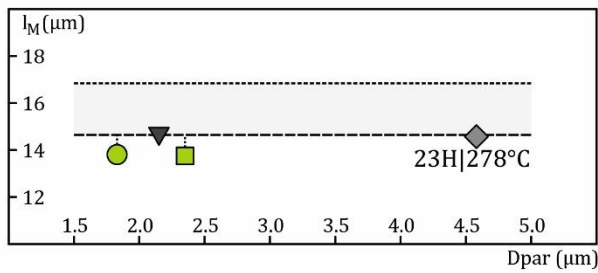
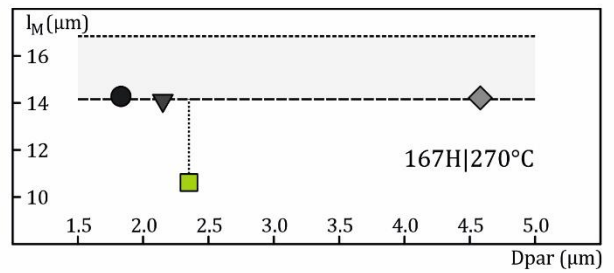
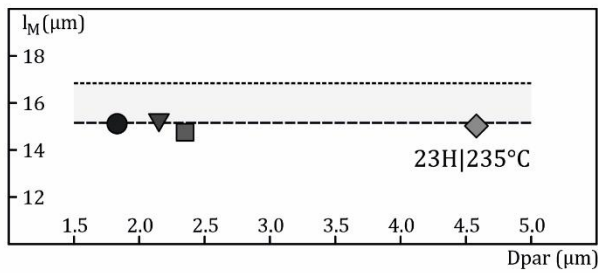
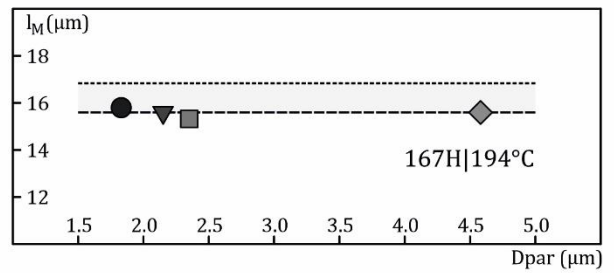
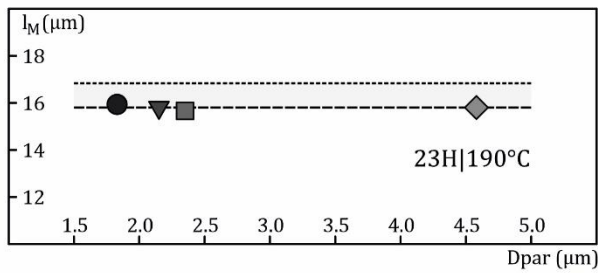
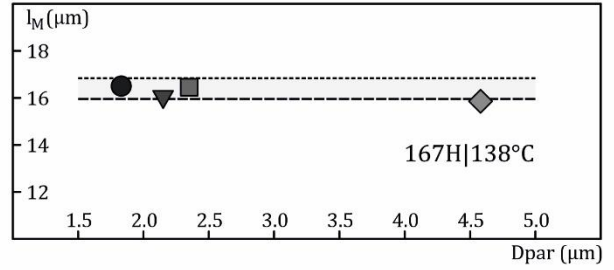
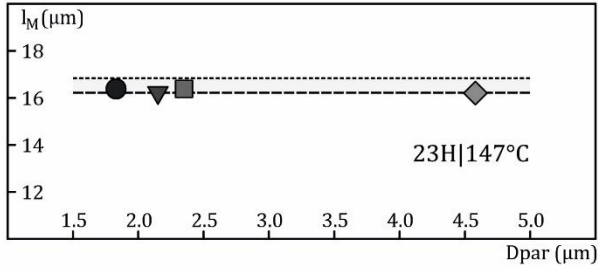


Figure S1(c)

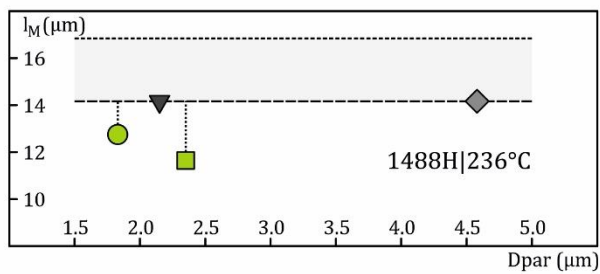
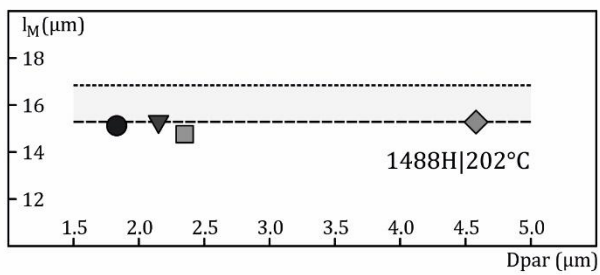
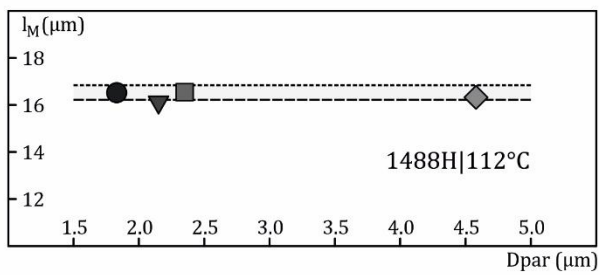
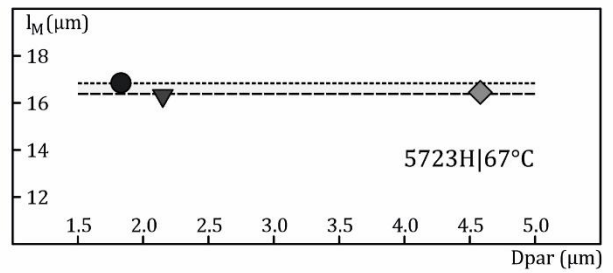
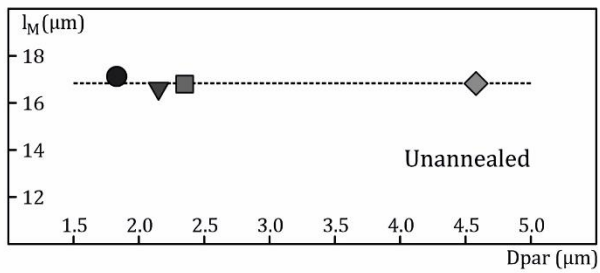
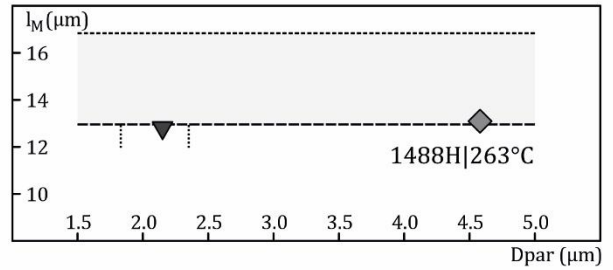
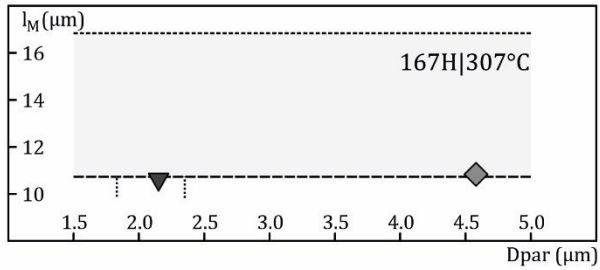


Figure S1(c)

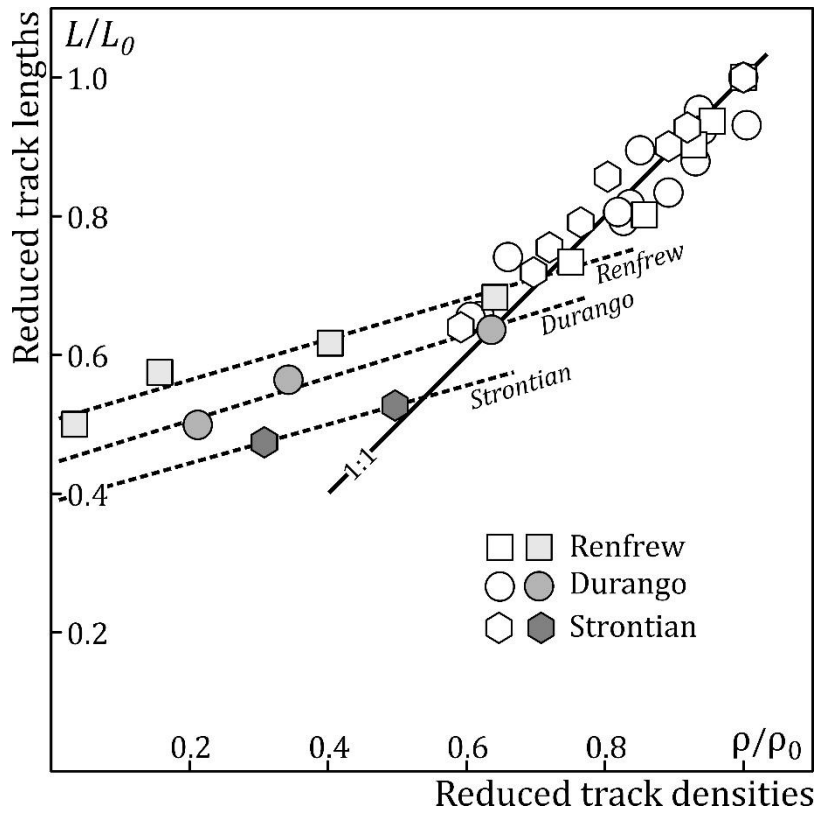


Figure S2

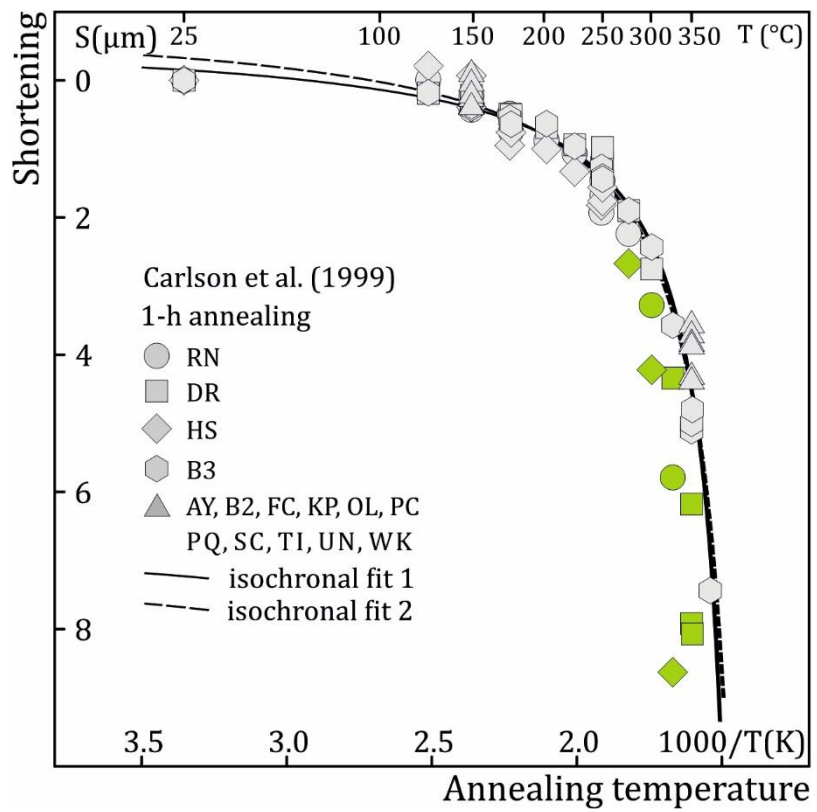


Figure S3(a)

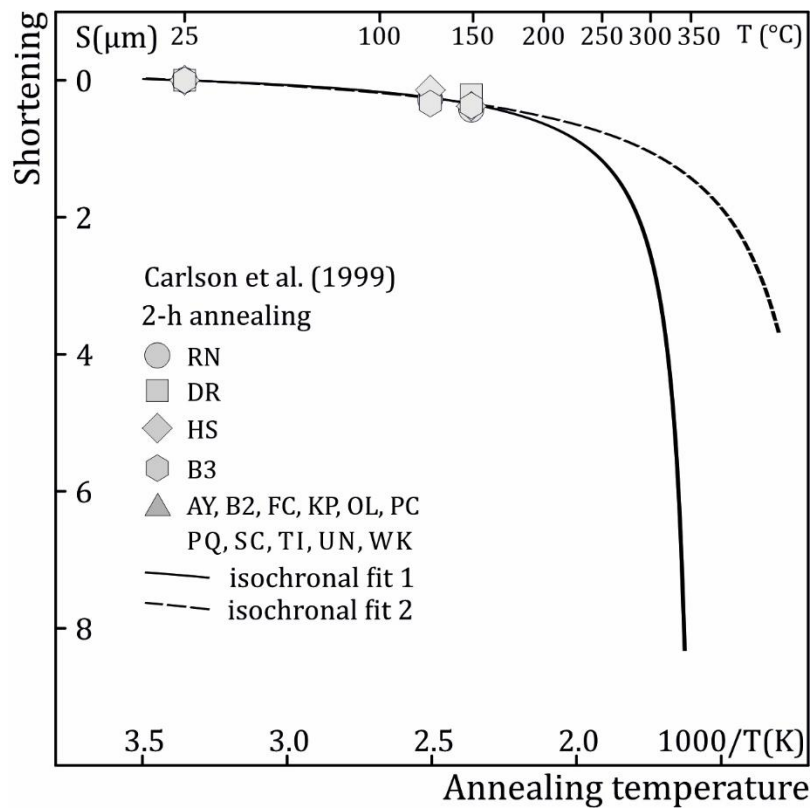


Figure S3(a)

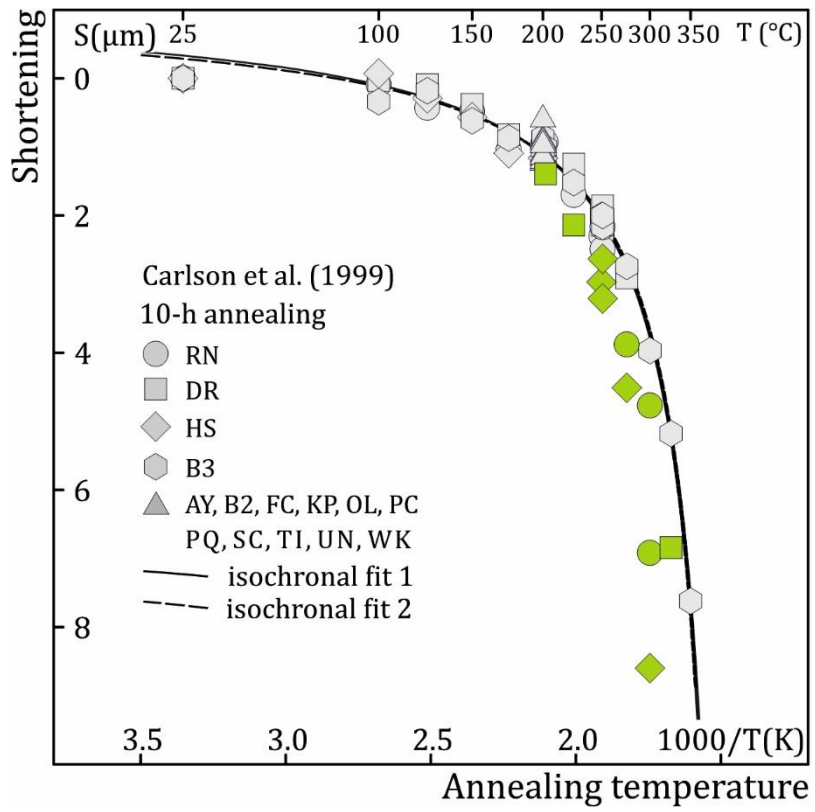


Figure S3(a)

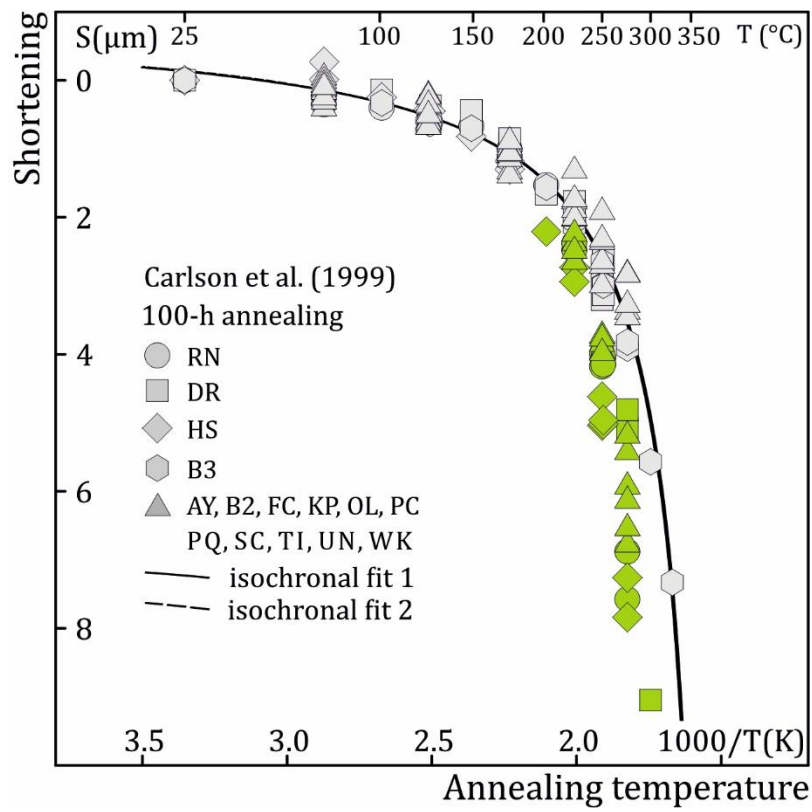


Figure S3(a)

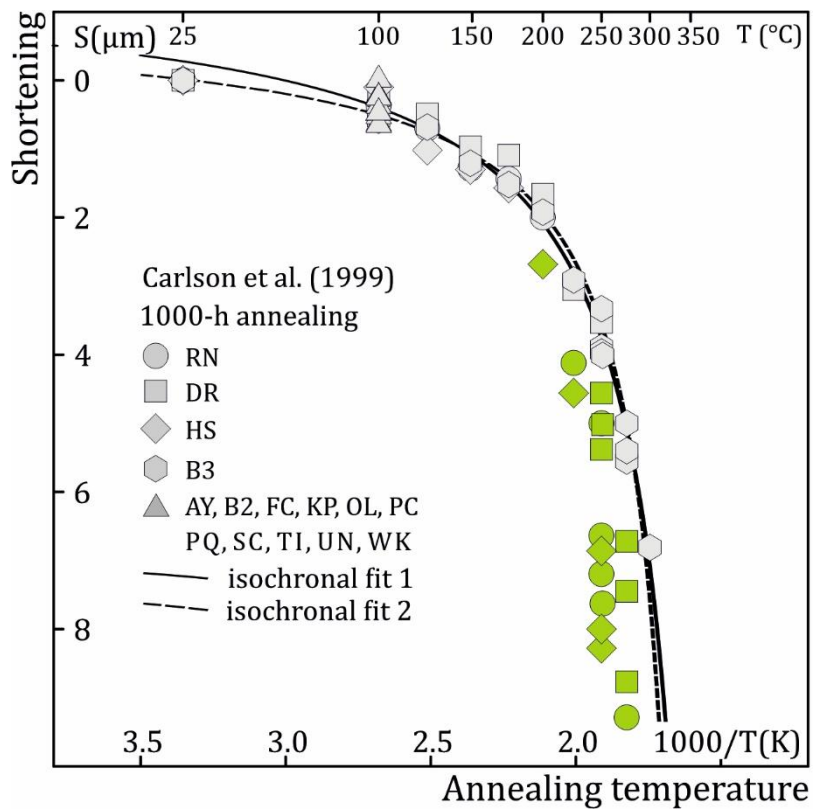


Figure S3(b)

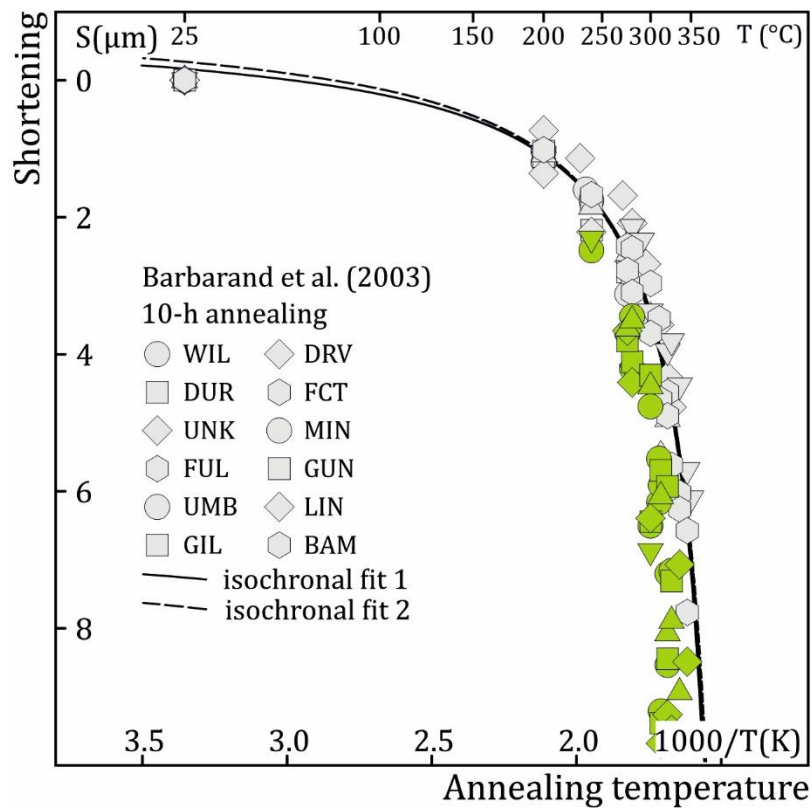


Figure S3(b)

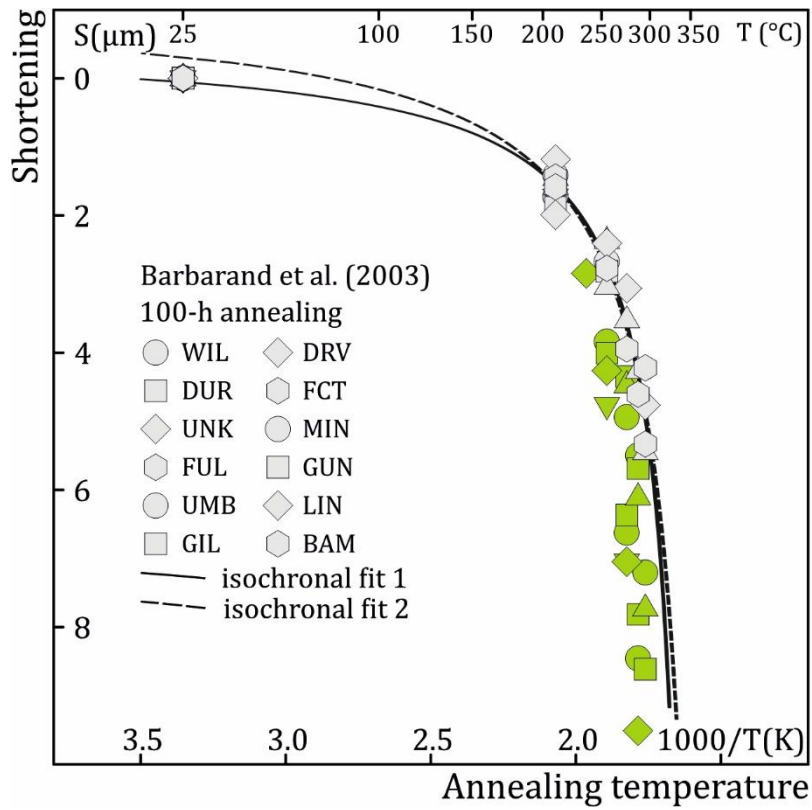


Figure S3(b)

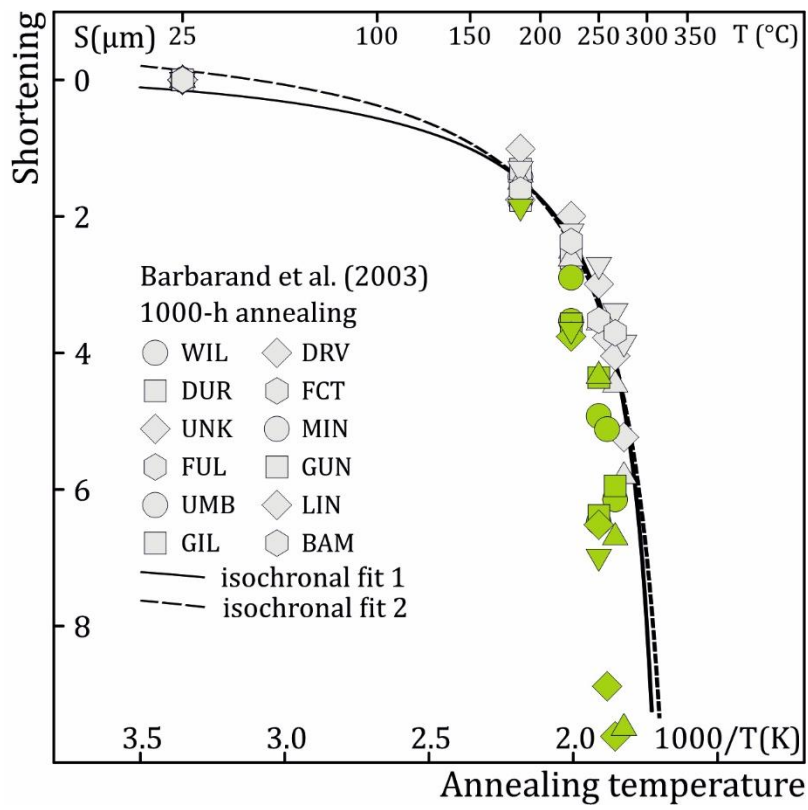


Figure S3(c)

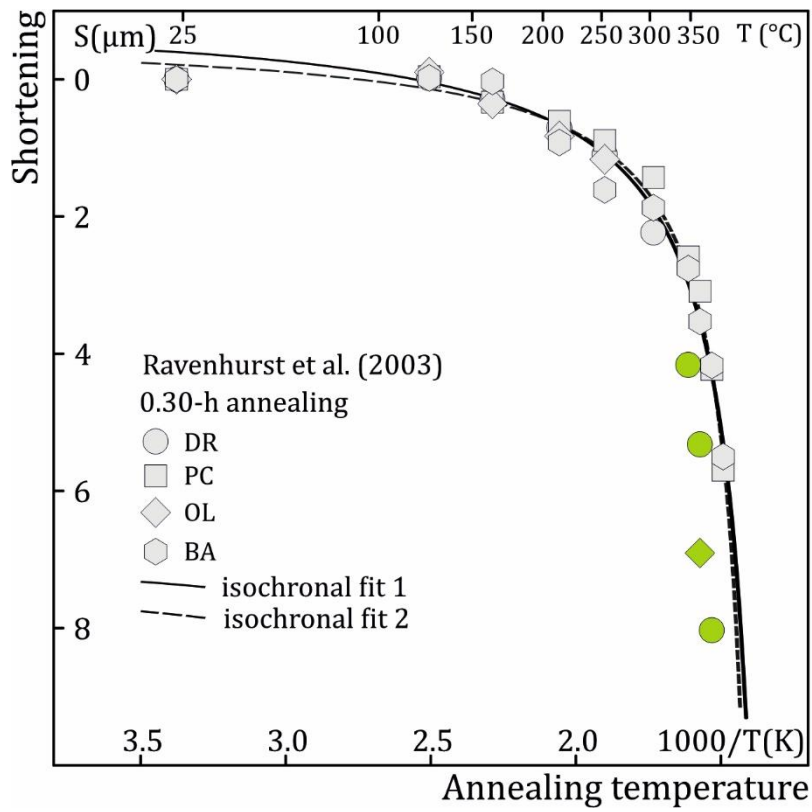


Figure S3(c)

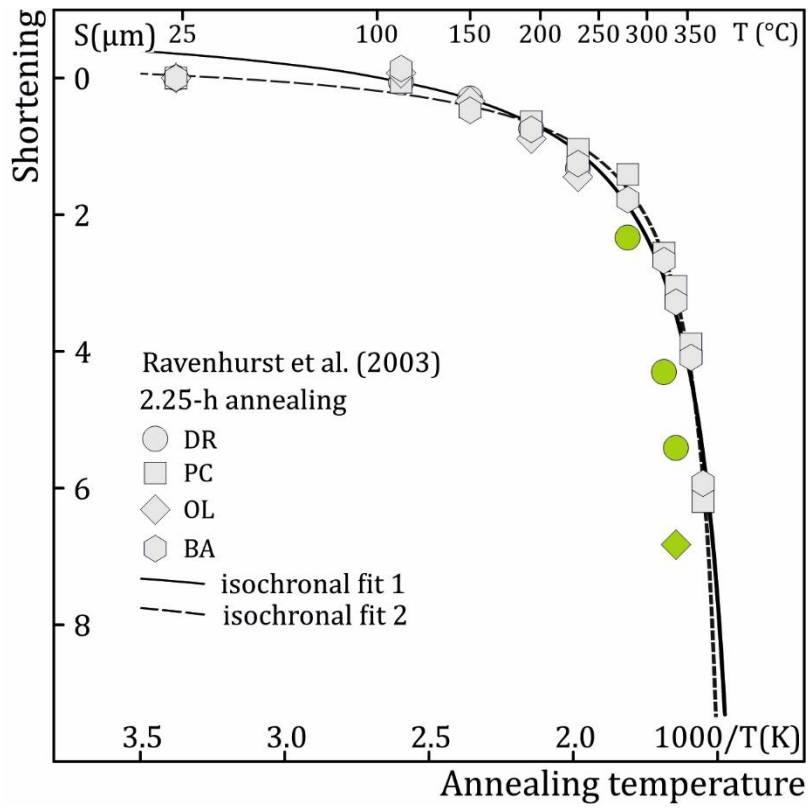


Figure S3(c)

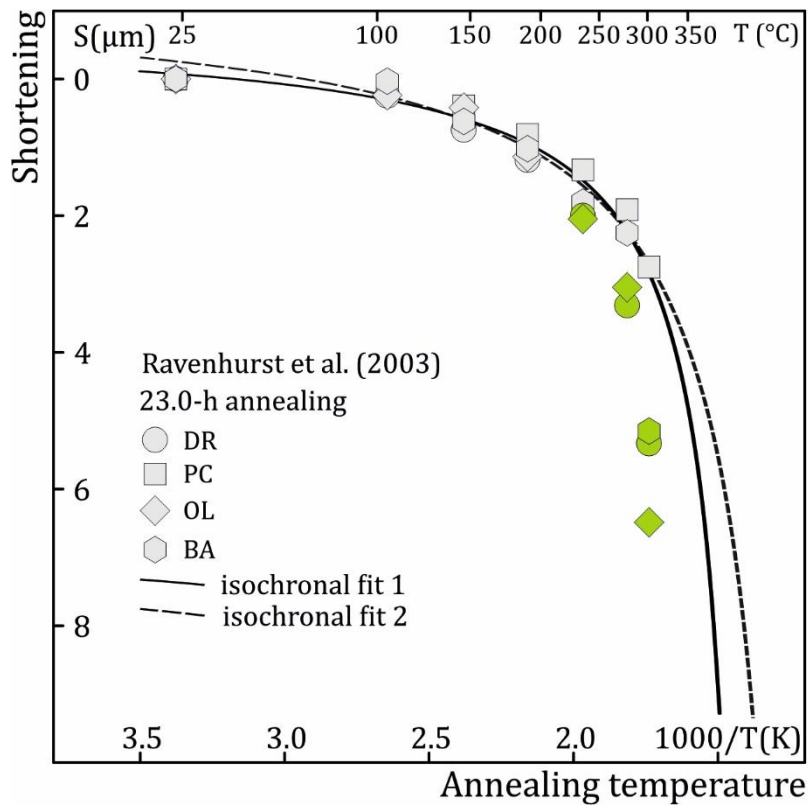


Figure S3(c)

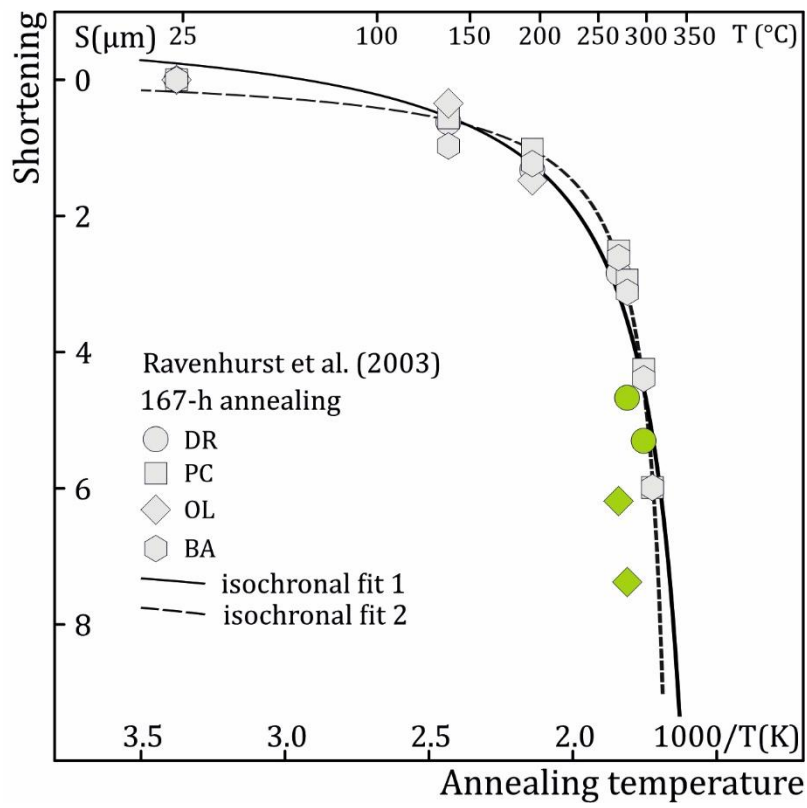


Figure S3(c)

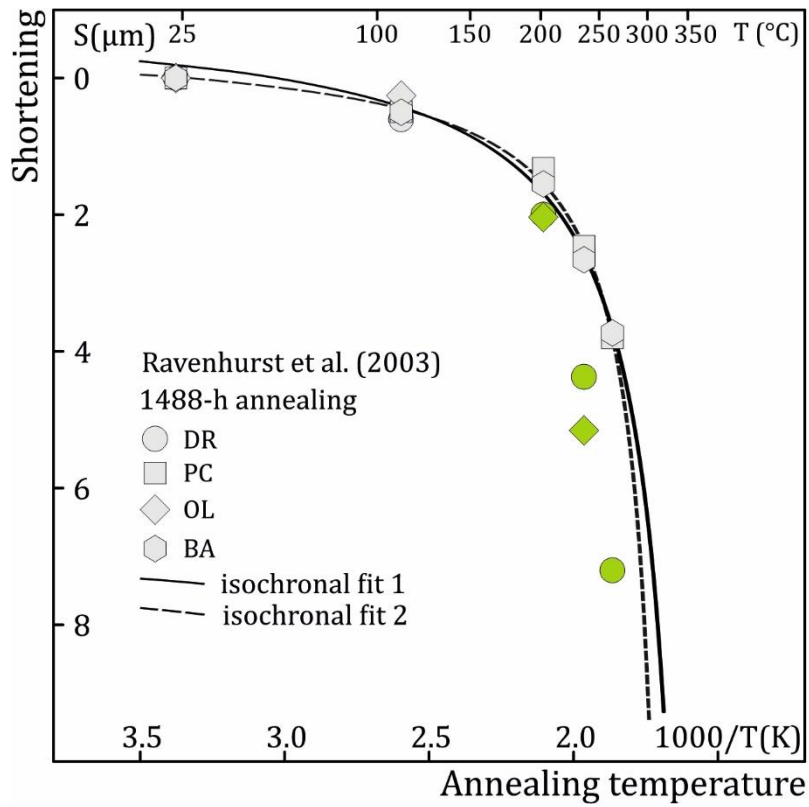


Figure S3(c)

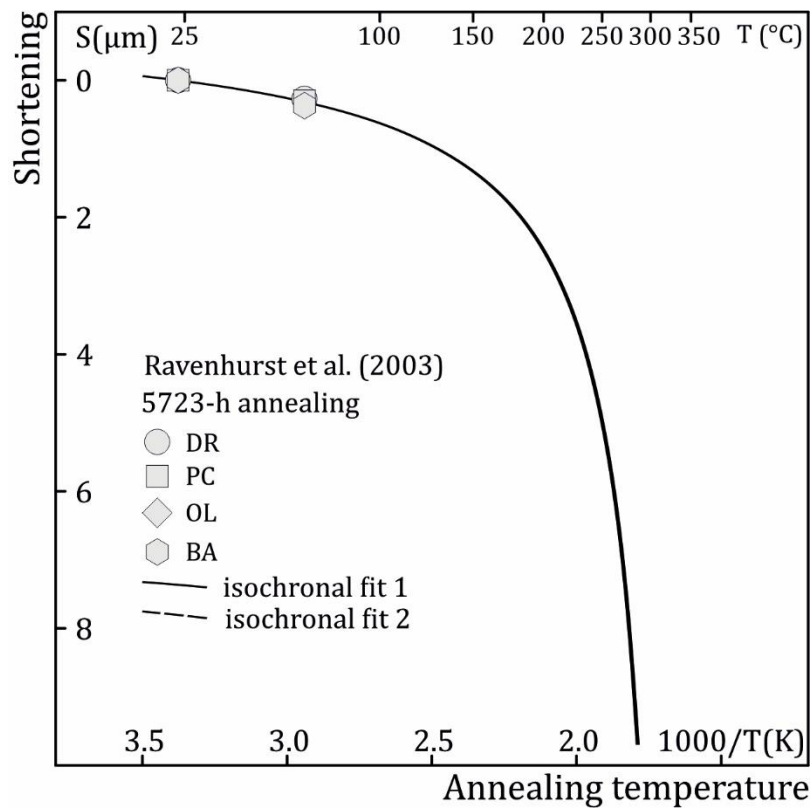


Figure S3(c)

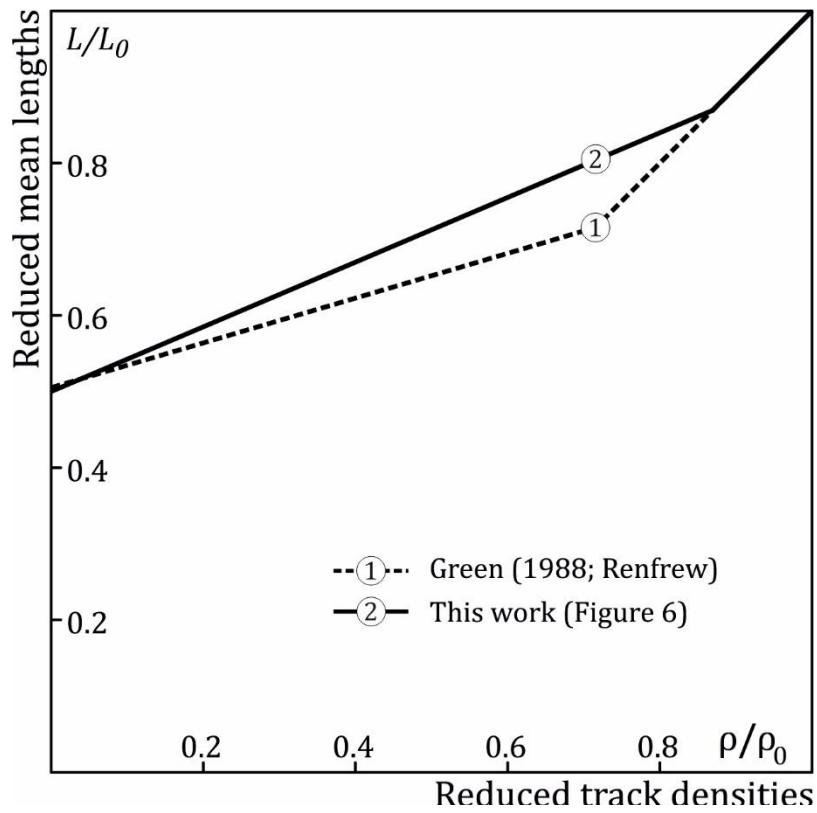


Figure S4