Tectonics

Supporting Information for

Changing patterns of exhumation and denudation in front of an advancing crustal indenter, Tauern Window (Eastern Alps)

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Introduction S1

Reconstructing the orogenic crust in the Tauern Window area during Indentation (Fig. 7).

The starting point for the reconstruction in Figure 7 is the present-day surface geology (Fig. 7c) in the tectonic map of the Tauern Window of *Schmid et al.* [2013, their Fig. 1]. This map is also representative of the situation some 11 Ma [*Fügenschuh et al.*, 1997], when the Brenner Normal Fault became inactive and lateral escape tectonics affected domains towards the Pannonian Basin, east of the map view. GPS studies indicate some ongoing lateral escape in response to ongoing Adria indentation [*Vrabec et al.*, 2006], but this is very slow [1-2 mm/yr, e.g., *Bada et al.*, 2007; see other references in *Scharf et al.*, 2013a; *Schmid et al.*, 2013; *Rosenberg and Garcia*, 2011].

Text S1.

Map for 21 Ma:

The Adriatic indenter front is presumed to have begun its fast northward movement in Early Miocene time as constrained by two events that are kinematically linked in space and time: (1)

the onset of rapid exhumation in the western Tauern Window at ~20 Ma as indicated by thermal modeling of isotopic cooling ages in the western Tauern Window [*Fügenschuh et al.*, 1997]; (2) the onset of thrusting within the Adriatic Indenter at 23-21 Ma based on biostratigraphic ages [*Luciani and Silvestrini*, 1996; *Luciani et al.*, 1989] of the youngest sediments in the footwall of a major, SE-directed thrust in the Giudicarie Belt [*Scharf et al.*, 2013a; *Schmid et al.*, 2013]. The structure linking motions in (1) and (2) is a transpressive bridge system of upright folds and shear zones in the western Tauern Window (Fig. 7b) which transferred northward motion of the indenter to eastward lateral escape of orogenic crust between the SEMP and Periadriatic faults [*Scharf et al.*, 2013a; *Schneider et al.*, submitted]. In this system, the northwestern tip of the indenter functioned as a kinematic singularity point.

The total offset along the Giudicarie Belt that accommodated Adriatic indentation of the Eastern Alps is debated to range from 15 [Viola et al., 2001] to 87 km [Schonborn, 1992]. In this reconstruction we use an offset of 75 km (Fig. 7c) which is close to values published by previous authors [77 km, Laubscher, 1988; 80 km, Frisch et al., 2000 and Linzer et al., 2002]. The 75 km estimate is based on the offset of the Periadriatic Fault, which is assumed to have been straight and WNW-ESE trending prior to latest Oligocene time [Fig. 7a, *Pomella et al.*, 2012]. The total offset includes about 28 km of late Oligocene-earliest Miocene northward displacement and counterclockwise rotation of the Meran-Mauls Fault (MM). Therefore, we use an offset of 47 km since 21 Ma (Fig. 7b).

The total sinistral offset along the SEMP in Figure 7a is estimated to be 65 km as obtained by restoring the tips of the grey unit on either side of this fault to their originally contiguous position (Innbruck and Wagrain Quartzphyllite units of the Silvretta-Seckau Nappe System, *Pestal et al.*, 2009). This is within the 60-70 km range of displacements proposed by previous workers and includes 6 km of sinistral displacement on the Königsee-Lammertal-Traunsee Fault [*Decker et al.*, 1994 in *Schmid et al., 2013*; fault not shown on any figures here]. The timing of motion on the SEMP in the Tauern Window area is well constrained by widely ranging mica ages to be early Oligocene to mid-Miocene [Fig. 8, *Urbanek et al.*, 2002; *Glodny et al.*, 2008], whereas eastern segments of this fault (Hochschwab Karst Massif – Styria, Austria) may still be active [U/Th dating of offset speleothems in caves along the fault, *Plan et al.*, 2010]. We estimate post-21 Ma sinistral displacement to be 32 km (Fig. 7b) as obtained by repositioning the Innbruck and Wagrain Quartzphyllite units of the Silvretta-Seckau Nappe (*Pestal et al.*, 2009) on either side of the SEMP in the following way: (1) the block northeast of the Tauern Window and immediately south of the SEMP is restored some 43 km eastward from its present location, an amount equal to the difference of ~54 km of east-west, orogen-parallel motion due to extension on the Brenner and Katschberg normal faults (see below) and 12 km of offset required to close the mid-Miocene Tamsweg pull-apart basin [17-14 Ma, *Zeilinger*, 1997 in *Scharf et al.*, 2013a] along the sinistral Niedere Tauern Fault System (NF, Figs. 7b, c); (2) the adjacent block north of the SEMP is restored 22 km to the SE, which is taken to be equal to the minimum amount of Miocene sinistral motion on the Inntal Fault. The timing of motion on this fault is also poorly constrained, but *Ortner et al.* [2006] indicates that most of the maximum 40 km of sinistral displacement is post-Oligocene.

Extensional displacement on the Katschberg Normal Fault is taken to be 23 km in map view, a conservative estimate from the 23-29 km range of horizontal displacements provided by *Scharf et al.* [2013a]. Estimates of extensional displacement accommodated by the Brenner Normal Fault and upright folds and shear zones in its footwall range from 2 to 42 km [*Behrmann*, 1988; *Selverstone*, 1988; *Rosenberg and Garcia*, 2011; *Fügenschuh et al.*, 2012]; in our reconstruction we used an average value of 20 km.

The Drau-Möll Block south of the Mölltal Fault is displaced to the west along the Pustertal-Gailtal segment of the Periadriatic Fault and joins with the Rieserferner Block to form one large triangular zone with its apex just south of the narrow middle of the Tauern Window (Fig. 7b). This involves 20 km of motion on the Zwischenbergen-Wöllatratten and Drautal Faults [ZWD in Fig. 7; *Exner*, 1962c; *Heinisch and Schmidt*, 1984; *Schmid et al.*, 2013] to restore the Ragga-Teuchl Fault [RT in Fig. 7, *Hoinkes et al.*, 1999; *Scharf et al.*, 2013a] with its western continuation, the DAV Fault. Moving these blocks rigidly, we obtain a narrow gap along the western side of the Pustertal-Gailtal Fault between the indenter and the triangular zone. This gap probably reflects non-rigid behaviour (deformation) of the triangular zone that was accommodated by several strike-slip and thrust faults within the blocks [e.g. *Hoke*, 1990; *Schuster et al.*, 2015].

Part of the Sonnblick and Hochalm subdomes had already cooling to below 300°C while the western Tauern Dome was still forming at temperatures of ~ 500 °C [*Reddy et al.*, 1993; *Luth and Willingshofer*, 2008; *Schneider et al.*, 2013; *Favaro et al.*, 2015]. Thermal modeling of the WTD indicates that the onset of rapid exhumation preceded rapid cooling at 20 Ma by some 2 Ma [*Fügenschuh et al.*, 1997] and coincided in time with this stage of orogenic indentation [*Pomella et al.*, 2011, 2012; *Schmid et al.*, 2013]. Zircon fission track ages indicate that cooling of both subdomes to below 240°C, which corresponds to the transition from viscous to frictional (brittle) deformation in quartz-rich rocks [*Handy et al.*, 1999; *Stipp et al.*, 2002] occurred no later than 17-15 Ma [*Dunkl et al.*, 2003; *Wölfler et al.*, 2008; *Bertrand*, 2013].

Map for 30 Ma

The ages in Figure 8 show that the first stage of indentation started between 30 and 25 Ma, after the emplacement of the Adamello intrusion between 42 and 30 Ma [*Brack*, 1985; *Del Moro et al.*, 1985b], together with the activity of the SEMP, Meran Mauls and DAV faults [*Wagner et al.*, 2006; *Frost et al.*, 2009; *Mancktelow et al.*, 2001; *Schneider et al.*, 2013]. During this incipient stage of indentation the restoration of the Adriatic Indenter is based on the horizontalization and backrotation of the Meran Mauls Fault to join the northern Pustertal-Gaital Fault (norther boundary of the Adriatic Indenter) with the Tonale Fault [central segment of the Periadriatic Fault, *Laubscher*, 1988; *Stipp et al.*, 2004; *Pomella et al.*, 2012].

To restore the 28 km remaining from the previous restoration step to reach the total sinistral offset of 75 km along the Giudicarie Belt, we back-rotated the Meran-Mauls Fault (MM; see Fig. 7b) which was active as a transpressional restraining bend sometime between 31 and 15 Ma according to Ar/Ar dating of pseudotachylite in small Periadriatic intrusive lenses arrayed along this fault [*Pomella et al.*, 2010, 2011; *Müller et al.*, 1998, 2001; *Prosser*, 1998].

These small Periadriatic intrusives (collectively termed "Tonalitic Lamella") along the Meran-Mauls Fault are interpreted as slivers of the the Adamello batholith that were sheared and rotated counter-clockwise together with the Meran-Mauls Fault [*Martin et al.*, 1993; *Morten*, 1974; *Pomella et al.*, 2011]. The Tonalitic Lamella is ~30 km long. To restore it to its original location along the northern margin of the Adamello batholith, we move all the blocks north of the originally straight Periadriatic Fault westward by about 30 km (Fig. 7a). The Periadriatic Fault System has an estimated dextral displacement of ~150 km [*Laubscher 1991*] and began strike-slip activity as early as 35-30 Ma to accommodate westward motion of the Adriatic Plate with respect to Europe during the Alpine collision [*Handy et al.*, 2015]. Unfortunately, Oligo-Miocene displacement estimates for the Pustertal-Gaital segment of the Periadriatic Fault are unavailable [*Bistacchi et al.*, 2010], but radiometric ages indicate continuous activity until 13 Ma [*Zwingmann and Mancktelow*, 2004].

The block south of the SEMP Fault is restored 30 km to the west with respect to its position at 21 Ma, yielding a total of 65 km of post-30 Ma sinistral motion on the SEMP (discussed above). The SEMP became active at 33-32 Ma [*Urbanek et al.*, 2002; *Glodny et al.*, 2008; *Schneider et al.*, 2013].

The DAV (Defereggen-Antholz-Vals) Fault is constrained by radiometric ages to have been active from 35 to 25 Ma [Borsi et al., 1979; Schulz, 1990; Most, 2003; Romer and Siegesmund, 2003], with focused activity within the period 33-31 Ma (Rb-Sr white mica formation ages of Müller et al., 2000, 2001), coincident with ~31 Ma emplacement of the Rieserferner Pluton

(Wagner et al. 2006). Mylonitic shearing on the DAV lasted no longer than 20 Ma (Wagner et al. 2006). The overall displacement during this time was sinistral based on mylonitic shear-sense indicators (Kleinschrodt 1987; Wagner et al. 2006), although Mancktelow et al. (2001) proposed a switch from sinistral to dextral motion at ~30 Ma. The amount of horizontal displacement on the DAV is unconstrained due to a lack of markers. Vertical, N-side up displacements along the DAV were considerable, as inferred from the jump in Alpine mica ages across the DAV (Schuster et al. 2005 and refs therein): ~25 km between 100 and 30 Ma and < 10 km between 30 and 20 Ma (Handy et al. 2005). The former displacement plays no role in our map reconstruction as it was probably related to pre- to early collisional exhumation. The latter, more modest displacement is attributed to exhumation and cooling of the tips of the subindenters during indentation (Handy et al. 2005).

Incipient indentation is well recorded within the Tauern Window, with the oldest formation ages of Sonnblick Subdome at temperatures greater than 500°C between 31 and 24 Ma [*Cliff et al.*, 1985; *Reddy et al.*, 1993; *Inger and Cliff*, 1994; *Glodny et al.*, 2008; *Cliff et al.*, 2015; *Favaro et al.*, 2015]. The Ahorn and Tux shear zones within the Western Tauern Dome were also active, with ages on syn-kinematic phengite and K-feldspar within the shear zones ranging between 32 and 10 Ma [*Urbanek*, 2002; *Peresson and Decker*, 1997a, b; *Glodny et al.*, 2008; *Schneider et al.*, 2013].

Introduction S2: Values used for the paleostrain analyses in Figure 6.

Table S2: Values used for the paleostrain analyses in Figure 6. MET - Metnitz Outcrop; MUL - Mühldorf Outcrop; TW - Outcrops of Penninic units at the SW margin of the Tauern Window in the Möll Valley

Fault-slip data			Input row data								
	Properties		Orientation		Orientation 1		Slip	Conf.	Weight	Activ.	Striae
Id	Format	Type	OriA	OriB	Ori1A	Ori1B	Sense	Level	Factor	Type	Intens
MET-1	11	1	79	160	21	246	N	P	2,0	2	2
MET-2	11	1	44	175	19	105	N	P	2,0	2	2
MET-3	11	1	86	159	13	248	N	P	2,0	2	2
MET-4	11	1	64	123	63	115	N	P	2,0	2	2
MET-5	11	1	78	130	26	46	N	P	2,0	2	2
MET-6	11	1	81	3	49	82	D	S	2,0	2	2
MET-7	11	1	64	3	24	80	D	S	2,0	2	2
MET-8	11	1	66	26	20	107	D	S	2,0	2	2
MET-9	11	1	85	333	44	58	D	P	2,0	2	2
MET-10	11	1	74	2	34	283	D	P	2,0	2	2
MET-11	11	1	89	100	52	11	X	X	2,0	2	2
MET-12	11	1	65	5	21	285	D	S	2,0	2	2
MET-13	11	1	89	23	18	293	S	S	2,0	2	2
MET-14	11	1	78	27	21	302	S	S	2,0	2	2
MET-15	11	1	60	132	19	53	N	S	2,0	2	2
MET-16	11	1	54	81	52	100	N	S	2,0	2	0
MET-17	11	1	56	88	54	108	N	S	2,0	2	0
MET-18	11	1	53	90	50	117	N	S	2,0	2	0
MET-19	11	1	59	105	58	122	N	S	2,0	2	0
MET-20	11	2	42	170	70	352		S	2,0	1	0
MET-21	11	2	53	127	66	312		S	2,0	1	0
MET-22	11	2	34	156	70	335		S	2,0	1	0
MET-23	22	1	141	21	117	19	N	S	2,0	2	0
MET-24	22	3	96	26	105	80		P	3,0	1	2
MET-25	22	1	154	31	120	27	N	S	2,0	2	0
MET-26	22	1	186	71	274	6	D	S	2,0	2	0
MET-27	22	1	247	54	320	22	S	S	1,0	2	0
MET-28	22	4	8	63			S	P	3,0	2	0
MET-29	22	1	52	88	322	8	S	S	1,0	2	0
MET-30	22	1	198	88	287	16	S	S	1,0	2	0
MET-31	22	1	233	79	320	15	S	S	1,0	2	0
MET-32	22	1	45	85	133	20	S	S	3,0	2	0
MET-33	22	1	165	40	163	40	N	C	3,0	2	2
MET-34	22	1	155	43	163	43	N	C	3,0	2	2
MET-35	22	4	153	53			D	S	3,0	2	0
MET-36	22	1	47	75	324	23	S	C	3,0	2	0

MET-37	22	4	75	47			N	S	3,0	2	0
MET-38	22	1	217	82	127	5	S	C	3,0	2	0
MET-39	22	1	225	74	306	28	S	C	3,0	2	0
MET-40	22	1	215	85	303	23	S	C	3,0	2	0
MET-41	22	1	188	85	100	19	S	C	3,0	2	0
MET-42	22	4	14	69			S	S	3,0	2	0
MET-43	22	1	33	67	311	19	S	C	3,0	2	0
MET-44	22	1	219	78	306	13	S	C	3,0	2	0
MET-45	22	1	180	90	90	0	S	S	3,0	2	0
MET-46	22	4	84	56			N	P	3,0	2	0
MET-47	22	1	48	78	322	19	S	C	3,0	2	0
MET-48	22	1	126	53	159	48	N	C	3,0	2	0
MET-49	22	1	228	83	318	2	S	S	3,0	2	0
MET-50	22	1	51	81	323	10	S	S	3,0	2	0
MET-51	22	1	27	76	108	32	S	S	3,0	2	0
MET-52	22	3	160	38	115	75		S	3,0	1	0
MET-53	22	1	56	85	11	83	S	C	3,0	2	2
MET-54	22	1	252	75	334	29	S	C	3,0	2	2
MET-55	22	1	20	81	292	10	N	C	3,0	2	2
MET-56	22	3	141	26	128	53		S	3,0	1	0
MET-57	22	4	3	79			S	S	3,0	2	0
MET-58	22	4	339	82			S	S	3,0	2	0
MUL-1	11	1	72	160	28	240	N	P	7,0	2	2
MUL-2	11	1	64	170	33	242	N	P	7,0	2	2
MUL-3	11	1	52	146	52	146	N	P	7,0	2	2
MUL-4	11	1	26	109	23	137	N	S	7,0	2	2
MUL-5	11	1	26	111	25	117	N	P	7,0	2	2
MUL-6	11	1	40	145	39	144	N	P	7,0	2	2
MUL-7	11	1	65	169	22	248	N	S	3,0	2	2
MUL-8	11	1	81	20	46	101	S	S	1,0	2	2
MUL-9	11	1	62	192	14	274	N	S	3,0	2	2
MUL-10	11	1	72	345	17	69	D	S	1,0	2	2
MUL-11	11	1	75	20	8	292	S	S	5,0	2	2
MUL-12	11	1	65	173	41	238	S	S	5,0	2	2
MUL-13	11	4	19	86			N	S	3,0	2	0
MUL-14	11	4	23	84			N	S	3,0	2	0
MUL-15	11	4	24	105			N	S	3,0	2	0
MUL-16	11	4	72	186			N	S	3,0	2	0
MUL-17	11	4	32	132			S	S	3,0	2	0
MUL-18	11	4	36	122			S	S	3,0	2	0
MUL-19	11	4	31	126			S	S	3,0	2	0
MUL-20	11	4	42	70			N	S	3,0	2	0
MUL-21	11	4	40	32			N	S	3,0	2	0
MUL-22	11	4	42	100			N	S	3,0	2	0
MUL-23	11	3	40	180	56	114		P	7,0	1	0
MUL-24	11	3	27	150	52	146		P	7,0	1	0

MUL-25	22	1	205	80	292	17	S	S	3,0	2	2
MUL-26	22	1	3	72	282	25	D	S	3,0	2	2
MUL-27	22	1	238	83	325	22	X	X	3,0	2	2
MUL-28	22	1	14	83	290	43	S	S	3,0	2	2
MUL-29	22	1	166	68	82	14	D	S	3,0	2	2
MUL-30	22	1	126	30	164	25	N	C	3,0	2	2
MUL-31	22	1	168	73	252	17	D	C	3,0	2	2
MUL-32	22	1	110	63	165	48	N	S	3,0	2	2
MUL-33	22	1	352	62	274	21	D	S	3,0	2	2
MUL-34	22	1	297	61	208	1	S	S	3,0	2	2
MUL-35	22	1	288	55	205	10	S	S	3,0	2	2
TW1	22	1	36	51	119	7	D	C	2,0	2	2
TW2	22	1	31	70	303	6	D	C	2,0	2	2
TW3	22	1	31	84	301	2	D	C	2,0	2	2
TW4	22	1	262	85	176	37	S	C	2,0	2	2
TW5	22	1	92	59	174	13	S	C	2,0	2	2
TW6	22	1	64	79	153	4	D	C	2,0	2	2
TW7	22	1	59	64	330	2	D	C	2,0	2	2
TW8	22	1	45	64	315	0	D	C	2,0	2	2
TW9	22	1	53	67	324	1	D	C	2,0	2	2
TW10	22	1	60	75	142	29	D	C	2,0	2	2
TW11	22	1	48	72	321	8	D	C	2,0	2	2
TW12	22	1	60	72	144	18	D	C	2,0	2	2
TW13	22	1	63	59	137	25	D	C	2,0	2	2
TW14	22	1	78	68	351	8	D	C	2,0	2	2
TW15	22	1	53	37	4	26	D	C	2,0	2	2
TW16	22	1	56	36	21	30	D	C	2,0	2	2
TW17	22	1	66	45	9	28	D	C	2,0	2	2
TW18	22	1	55	40	8	29	D	C	2,0	2	2
TW19	22	1	60	60	349	29	D	C	2,0	2	2
TW20	22	1	86	44	10	13	D	C	2,0	2	2
TW21	22	1	187	63	241	49	I	C	2,0	2	2
TW22	22	1	186	68	144	61	I	C	2,0	2	2
TW23	22	1	53	73	330	22	D	S	2,0	2	2
TW24	22	1	62	65	146	12	D	C	2,0	2	2
TW25	22	1	67	66	156	1	D	C	2,0	2	2
TW26	22	1	334	63	245	1	D	C	2,0	2	2
TW27	22	1	65	77	339	17	D	S	2,0	2	2
TW28	22	1	83	83	357	32	S	S	2,0	2	2
TW29	22	4	20	82			D	C	2,0	2	0
TW30	22	1	87	77	15	53	S	S	2,0	2	2
TW31	22	1	58	77	331	13	D	C	2,0	2	2
TW32	22	1	165	85	76	15	S	C	2,0	2	2
TW33	22	1	56	45	342	15	D	C	2,0	2	2
TW34	22	1	142	50	207	27	S	S	2,0	2	2
TW35	22	4	55	66			D	S	2,0	2	0

TW36	22	1	75	52	7	26	D	C	2,0	2	2	