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Supplemental Material

Table S1. Zircon U-Pb dating of the dacite samples from the upper Gazhacun Formation of the Namling Basin.

Table S2. $\delta^2\text{H}_{\text{alk}}$ values from the upper Gazhacun Formation of the Namling Basin.

Table S3. The Miocene $\delta^2\text{H}_w$ and $\delta^{18}\text{O}_w$ values of the paleometeoric water across the Tibetan Plateau (between 29°N and 40°N) derived from plant waxes/hydrous mica and authigenic carbonates.

Table A1. Zircon U-Pb dating of the dacite samples from the upper Gazhacun Formation of the Namling Basin.

Analysis	Corrected ratios										Corrected ages (Ma)						concordant ratio	Concordant ages (Ma)	1σ		
	$^{207}\text{Pb}/^{206}\text{Pb}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ	$^{208}\text{Pb}/^{232}\text{Th}$	1σ	$^{238}\text{U}/^{232}\text{Th}$	1σ	$^{207}\text{Pb}/^{206}\text{Pb}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ				$^{208}\text{Pb}/^{232}\text{Th}$	1σ
2015TX60																					
2015TX60-001	0.04605	0.00927	0.01453	0.00292	0.00229	0.00003	0.0008	0.00005	0.78	0.01		343	15	3	14.7	0.2	16	1	102	15	0.2
2015TX60-002	0.04605	0.02334	0.01526	0.00773	0.0024	0.00005	0.0009	0.00018	1.02	0.01		847	15	8	15.5	0.3	19	4	97	16	0.3
2015TX60-003	0.05009	0.00905	0.01605	0.00289	0.00232	0.00003	0.0007	0.00004	1.4	0.01	199	340	16	3	15	0.2	14.8	0.8	107	15	0.2
2015TX60-004	0.04605	0.00232	0.0162	0.00079	0.00255	0.00003	0.001	0.00007	0.83	0.01		109	16.3	0.8	16.4	0.2	20	2	99	16	0.2
2015TX60-005	0.04606	0.00148	0.01461	0.00046	0.0023	0.00002	0.0008	0.00002	1.97	0.02	1	67	14.7	0.5	14.8	0.1	15.3	0.5	99	15	0.1
2015TX60-006	0.04609	0.00221	0.01636	0.00077	0.00257	0.00003	0.0008	0.00002	1.59	0.02	2	103	16.5	0.8	16.6	0.2	16.6	0.4	99	17	0.2
2015TX60-007	0.04871	0.00231	0.01559	0.00072	0.00233	0.00002	0.0007	0.00001	1.01	0.01	134	90	15.7	0.7	15	0.1	15	0.2	105	15	0.1
2015TX60-008	0.0475	0.00165	0.01534	0.00051	0.00235	0.00002	0.0008	0.00001	0.81	0.01	74	60	15.5	0.5	15.1	0.1	15.2	0.2	103	15	0.1
2015TX60-010	0.04704	0.00276	0.01548	0.00089	0.00239	0.00002	0.0008	0.00002	1.86	0.02	51	110	15.6	0.9	15.4	0.1	15.4	0.4	101	15	0.1
2015TX60-012	0.04662	0.00231	0.01644	0.00079	0.00256	0.00003	0.0007	0.00001	0.81	0.01	30	81	16.6	0.8	16.5	0.2	14.7	0.2	101	17	0.2
2015TX60-013	0.04399	0.00181	0.01439	0.00057	0.00238	0.00002	0.0008	0.00001	1.76	0.02	-71	68	14.5	0.6	15.3	0.1	16	0.2	95	15	0.1
2015TX60-016	0.04605	0.00079	0.01408	0.00022	0.00222	0.00002	0.0008	0.00003	2.54	0.03		34	14.2	0.2	14.3	0.1	15.1	0.6	99	14	0.1
2015TX60-017	0.04743	0.00232	0.0168	0.0008	0.00258	0.00003	0.0009	0.00001	0.74	0.01	71	83	16.9	0.8	16.6	0.2	18.6	0.2	102	17	0.2
2015TX60-018	0.04605	0.00072	0.01557	0.0002	0.00245	0.00002	0.0009	0.00004	1.52	0.02		31	15.7	0.2	15.8	0.1	17.6	0.8	99	16	0.1
2015TX60-020	0.04605	0.0055	0.01638	0.00195	0.00258	0.00002	0.0009	0.00004	0.59	0.01		237	16	2	16.6	0.2	19	0.8	96	17	0.2
2015TX60-021	0.04627	0.00415	0.01605	0.00143	0.00252	0.00003	0.0008	0.00002	1.14	0.01	12	175	16	1	16.2	0.2	16.2	0.4	99	16	0.2
2015TX60-022	0.05005	0.00362	0.01818	0.00129	0.00264	0.00003	0.0009	0.00002	0.93	0.01	197	140	18	1	17	0.2	18.2	0.4	106	17	0.2
2015TX60-024	0.04972	0.00232	0.01575	0.00072	0.00231	0.00002	0.0008	0.00001	0.92	0.01	182	90	15.9	0.7	14.9	0.1	17	0.2	107	15	0.1
2015TX60-025	0.04633	0.00204	0.01551	0.00066	0.00244	0.00002	0.0009	0.00001	1.49	0.01	15	74	15.6	0.7	15.7	0.1	18	0.2	99	16	0.1
2015TX60-026	0.04703	0.00304	0.01606	0.00102	0.00249	0.00003	0.0009	0.00002	1.19	0.01	51	116	16	1	16	0.2	18	0.4	100	16	0.2
2015TX60-027	0.04629	0.00649	0.01574	0.00219	0.00247	0.00004	0.0009	0.00003	1.13	0.01	13	244	16	2	15.9	0.3	18.8	0.6	101	16	0.3
2015TX60-028	0.04606	0.00157	0.01412	0.00047	0.00222	0.00002	0.0007	0.00002	1.59	0.02	1	71	14.2	0.5	14.3	0.1	14.6	0.4	99	14	0.1
2015TX60-029	0.04141	0.00419	0.01463	0.00147	0.00257	0.00003	0.0008	0.00002	0.86	0.01	-210	164	15	1	16.5	0.2	15.8	0.4	91	17	0.2
2015TX60-030	0.04608	0.00727	0.01489	0.00233	0.00234	0.00004	0.0008	0.00003	0.7	0.01	2	283	15	2	15.1	0.3	15.2	0.6	99	15	0.3
Analysis	Corrected ratios										Corrected ages (Ma)						concordant ratio	Concordant ages (Ma)	1σ		
	$^{207}\text{Pb}/^{206}\text{Pb}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ	$^{208}\text{Pb}/^{232}\text{Th}$	1σ	$^{238}\text{U}/^{232}\text{Th}$	1σ	$^{207}\text{Pb}/^{206}\text{Pb}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ				$^{208}\text{Pb}/^{232}\text{Th}$	1σ
2015TX62																					
2015TX62-001	0.04804	0.00566	0.01495	0.00174	0.00226	0.00004	0.0007	0.00002	1.12	0.01	101	246	15	2	14.5	0.2	14.5	0.5	103	15	0.2
2015TX62-002	0.04725	0.00401	0.01486	0.00125	0.00228	0.00003	0.0007	0.00001	0.86	0.01	62	190	15	1	14.7	0.2	14.6	0.3	102	15	0.2
2015TX62-006	0.04606	0.0054	0.01434	0.00167	0.00226	0.00003	0.0007	0.00004	0.98	0.01	1	232	14	2	14.5	0.2	15	0.8	97	15	0.2

2015TX62-008	0.04605	0.02336	0.01311	0.00664	0.00206	0.00005	0.0007	0.00011	0.96	0.01		849	13	7	13.3	0.3	14	2	98	13	0.3
2015TX62-014	0.04605	0.02648	0.01192	0.00685	0.00188	0.00006	0.0007	0.00017	1.04	0.01		972	12	7	12.1	0.4	15	3	99	12	0.4
2015TX62-015	0.04605	0.00835	0.01421	0.00257	0.00224	0.00002	0.001	0.00011	0.98	0.01		313	14	3	14.4	0.2	21	2	97	14	0.2
2015TX62-016	0.04815	0.0046	0.01517	0.00143	0.00228	0.00003	0.0007	0.00001	0.8	0.01	107	212	15	1	14.7	0.2	14.6	0.3	102	15	0.2
2015TX62-017	0.04746	0.00558	0.01542	0.0018	0.00236	0.00003	0.0008	0.00002	1.21	0.01	72	227	16	2	15.2	0.2	15.6	0.4	105	15	0.2
2015TX62-018	0.04755	0.00629	0.01609	0.00212	0.00245	0.00003	0.0008	0.00004	1.3	0.01	77	264	16	2	15.8	0.2	15.8	0.8	101	16	0.2
2015TX62-019	0.04841	0.02211	0.01561	0.00711	0.00234	0.00007	0.0006	0.0001	1.53	0.02	119	732	16	7	15.1	0.5	13	2	106	15	0.5
2015TX62-020	0.04605	0.00869	0.01294	0.00242	0.00204	0.00005	0.0008	0.00014	1.2	0.01		323	13	2	13.1	0.3	16	3	99	13	0.3
2015TX62-021	0.04678	0.00408	0.01497	0.00129	0.00232	0.00003	0.0007	0.00002	1.15	0.01	38	193	15	1	14.9	0.2	14.9	0.4	101	15	0.2
2015TX62-022	0.05022	0.00595	0.01567	0.00184	0.00226	0.00004	0.0007	0.00002	1.2	0.01	205	264	16	2	14.6	0.2	14.4	0.3	110	15	0.2
2015TX62-027	0.04916	0.00802	0.01699	0.00276	0.00251	0.00004	0.0008	0.00004	1.28	0.01	156	309	17	3	16.1	0.2	16	0.8	106	16	0.2
2015TX62-028	0.04807	0.01054	0.01639	0.00358	0.00247	0.00005	0.0008	0.00005	1.01	0.01	103	381	17	4	15.9	0.3	16	1	107	16	0.3
2015TX62-030	0.04688	0.00718	0.01591	0.00242	0.00246	0.00004	0.0006	0.00003	1.16	0.01	43	260	16	2	15.8	0.3	12.7	0.6	101	16	0.3

Table A2. $\delta^2\text{H}_{\text{alk}}$ values from the upper Gazhacun Formation of the Namling Basin.

Sample #	amplitude C27 mv	amplitude C29 mv	amplitude C31 mv	$\delta^2\text{H}_{\text{C27}}$ ‰	$\delta^2\text{H}_{\text{C29}}$ ‰	$\delta^2\text{H}_{\text{C31}}$ ‰	CPI ₂₅₋₃₃	Pr/Ph	C ₃₀ $\beta\alpha$ /C ₃₀ $\alpha\beta$
NML21	4750	5045	1953	-231.7	-227.9	-220.7	2.1	3.4	0.56
NML22	4312	4492	1888	-247.3	-240.5	-230.1	2.5	3.4	0.57
NML23	5380	5462	3125	-233.5	-240.5	-236.4	2.3	2.6	0.53

Table A3. The Miocene $\delta^2\text{H}_w$ and $\delta^{18}\text{O}_w$ values of the paleometeoric water across the Tibetan Plateau (between 29°N and 40°N) derived from plant waxes/hydrous mica and authigenic carbonates.

Location/Samples	Age (Ma)	Latitude (°N)	$\delta^2\text{H}_{\text{alk}}$ (C_{29}) (VSMOW, ‰)	$\delta^2\text{H}_{\text{w}}$ (SMOW, ‰) ^a	$\delta^{18}\text{O}_{\text{c}}$ (PDB, ‰)	$\delta^{18}\text{O}_{\text{w}}$ (SMOW, ‰) ^b	Vegetation characters	Reference
Namling Basin							All the fossil forms are cool temperate deciduous woodlands. comprising 7 families, 10 genera and 22 species in total. Acer, Alnus, Salix, Betula, and Corylus are predominant	This study; Currie et al., 2016; Spicer et al., 2003; Khan et al., 2014
NML21	15	29.6	-227.9±1	-130.5±20	-17.9	-17.9±1.3		
NML22	15	29.6	-240.5±1	-144.4±20	-18.3	-18.3±1.3		
NML23	15	29.6	-240.5±1	-144.7±20	-18.3	-18.3±1.3		
618G	15	29.6	-266±1	-173±20				
618F	15	29.6	-261±1	-168±20				
618E	15	29.6	-267±1	-175±20				
618B	15	29.6	-254±1	-160±20				
Average				-157±30				
Lunpola Basin							temperate vegetation. mixed coniferous–broadleaved forests	Polissaret al., 2009; Sun et al., 2014
301	18-14	32	-230±3	-133±20	-8.9	-11.6±1.2		
299C	18-14	32	-219±11	-120±25	-0.4	-3.1±1.2		
299A	18-14	32	-236±1	-140±20	-6.7	-9.4±1.2		
Average				-131±32				
Hoh Xil Basin							temperate vegetation. Mixed broadleaves-coniferous and shrub (barberry);	Polissaret al., 2009; Sun et al., 2015; Li et al., 2015
158C	17-14	34.5	-204±1	-114±20	-7.4	-9.5±1.2		
158A	17-14	34.5	-203±1	-102±20				
157	17-14	34.5	-198±1	-97±20	-5.2	-7.3±1.2		
156D	17-14	34.5	-200±1	-99±20				
156B	17-14	34.5	-201±1	-100±20	-8.1	-10.2±1.2		
Average				-102±22				
Qaidam Basin							conifer mixed with lower abundant of broad leaves	Zhuang et al., 2014; Miao et al., 2013
07HTB045	15	37	-118±0.4	-18±20				
07HT009	15	37	-134±6.2	-36±22				
07HT056	15	37	-144±0.4	-47±20				
07HT082	14	37	-143±0.2	-46±20				
07HT113	13.5	37	-151±0.5	-55±20				
07HT122	13	37	-155±2.7	-59±20				
Average				-43±25				
Mount Everest							Gebélin et al., 2013	
leucogranite	17-15	28.1		-56±5				
pegmatite	17-15	28.1		-124±5				
bt-schist	17-15	28.1		-137±5				
calc-silicate	17-15	28.1		-140±5				
calc-silicate	17-15	28.1		-156±5				
leucogranite	17-15	28.1		-150±5				
calc-silicate	17-15	28.1		-142±5				
leucogranite	17-15	28.1		-137±5				
leucogranite	17-15	28.1		-94±5				
calc-silicate	17-15	28.1		-154±5				
bt-schist	17-15	28.1		-130±5				
bt-schist	17-15	28.1		-119±5				
bt-schist	17-15	28.1		-99±5				
bt-schist	17-15	28.1		-102±5				
bt-schist	17-15	28.1		-102±5				
bt-schist	17-15	28.1		-60±5				
calc-silicate	17-15	28.1		-57±5				
bt-gneiss	17-15	28.1		-52±5				
bt-gneiss	17-15	28.1		-64±5				
Most negative				-156±5				

a. Paleometeoric water δD_w values are calculated by applying the average established and local apparent fractionation factor of $-111\pm14\text{‰}$ in the Namling, Lunpola and Hoh Xil basins and -102‰ in the Qaidam Basin (Zhuang et al., 2014).

b. Paleometoric water $\delta^{18}\text{O}_w$ values are calculated by the calcite-water equation ([Kim and O'Neil, 1997](#)) with carbonate forming temperatures of $14.6\pm 3.6^\circ\text{C}$ in the Namling Basin, Lunpola Basin and Hoh Xil Basin. Uncertainties are expressed by 1 standard error of the mean ([Deng et al., 2012](#); [Sun et al., 2015](#); [Ingalls et al., 2018](#)).