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Experimental investigation of basaltic melt-felsic crust reaction: Implications for zero-age rhyolite genesis and felsic crust reworking



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Magma-rock interactions involve open-system processes where rocks undergo partial melting, minerals dissolve into the melt, and magmas hybridize. In this context, it is poorly understood how felsic rocks characterized by low- $\delta^{18}\text{O}$, similar to hydrothermally altered crust, form through reactions with basaltic magma or by the differentiation of hybridized magma. Our aim was to understand the consequences of low- $\delta^{18}\text{O}$ -felsic crust interacting with basaltic melt in shallow crustal settings and to explain the origin of low- $\delta^{18}\text{O}$ rhyolite and associated glasses encountered within the active Krafla volcano (KJ-39 and IDDP-1), Northern Iceland (Figure 1).

Here, we report the results of an experimental study on the rate and mechanism of the reaction between anhydrous Fe-Ti tholeiite basaltic melt and felsic granophyre rock at 1250°C and 0.2 GPa, water activity, $a_{\text{H}_2\text{O}} = 0$ and with oxygen fugacity fixed by the QFM (quartz-fayalite-magnetite) mineral buffer. We applied SEM, HR-EPMA and HR-SIMS as the micro-analytical methods to investigate the experimental and natural phases.

Our experiments (Table 1) reveal that the granophyre rock partially melts and dissolves (Figure 2), with the dissolution controlled by Si diffusion into basaltic melt. Comparing the major element and oxygen isotope chemistry of the Krafla glasses with the partial and interface melts produced in our experiments shows similarity (Figures 3-4, Table 2). Our data suggest that zero-age rhyolites are likely produced through partial melting of quartz-feldspar-rich granophyre rocks, accompanied by hybridization driven by silica diffusion in the basaltic magma (Figure 5). If the dissolution of felsic rock in basaltic magma reservoir were uniquely diffusion-controlled and restricted to interaction along the interface, very slow hybridization of the interface melt with basaltic melt would occur (Figure 6).

We propose that to produce the natural glasses observed in boreholes KJ-39 and IDDP-1 of Krafla volcano, the parental granophyre rock was progressively melted due to interaction with a hot basaltic magma (Figure 7), allowing the formation of chemically heterogeneous magma, which was sampled in 2008 and 2009 on the same depths by drilling (Figures 3-4, Table 2).

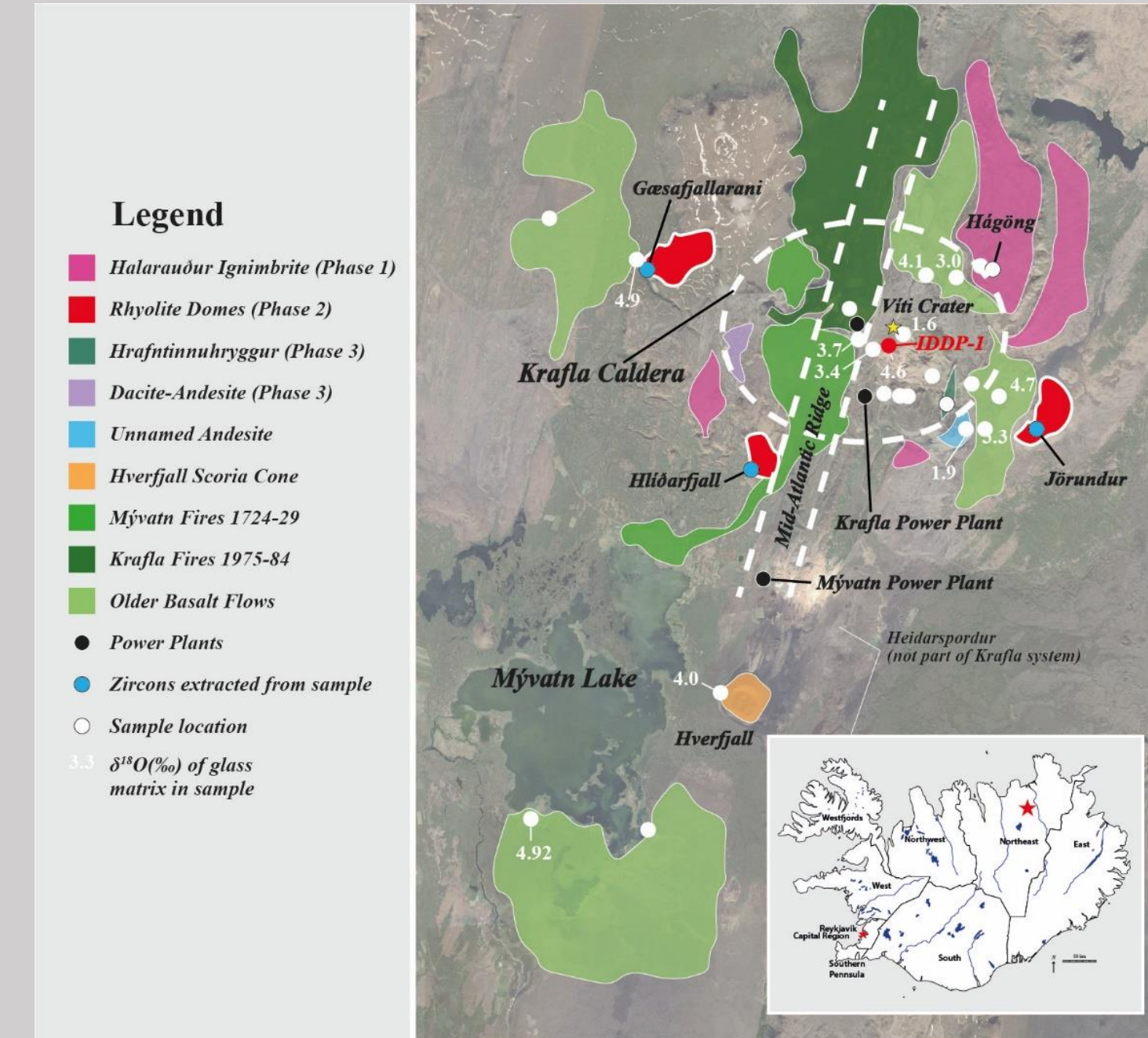


Figure 1. Geological map showing the Krafla caldera that is located in the Northeastern Iceland (see insert map) (after Hampton et al., 2021). The location of the IDDP-1 well and the Viti Crater are shown.

Table 1. Experimental parameters and results of the basaltic melt-granophyre rock reaction runs at dry conditions ($a_{\text{H}_2\text{O}} = 0$)

Run number	Design	Duration (min)	Pressure (GPa)	Temperature (°C)	Basalt/rock mass ratio	Resulting phases
(I) Stable configuration (diffusion-driven)						
18	I	10	0.2	1250	7.56	SIL _{Felsic} , SIL _{Fe-rich} , granophyre partially melted and dissolved
19	I	10	0.2	1250	4.65	see 18
110	I	10	0.2	1250	2.19	see 18
111	I	10	0.2	1250	2.86	see 18
(II) Unstable configuration (convection-driven)						
13	II	60	0.2	1250	7.60	Granophyre rock is melted and dissolved in the SIL _{Bas}
12	II	120	0.2	1250	9.07	see 13
15	II	300	0.2	1250	8.83	see 13
14	II	1440	0.2	1250	9.15	see 13
17	II	3480	0.2	1250	8.32	see 13

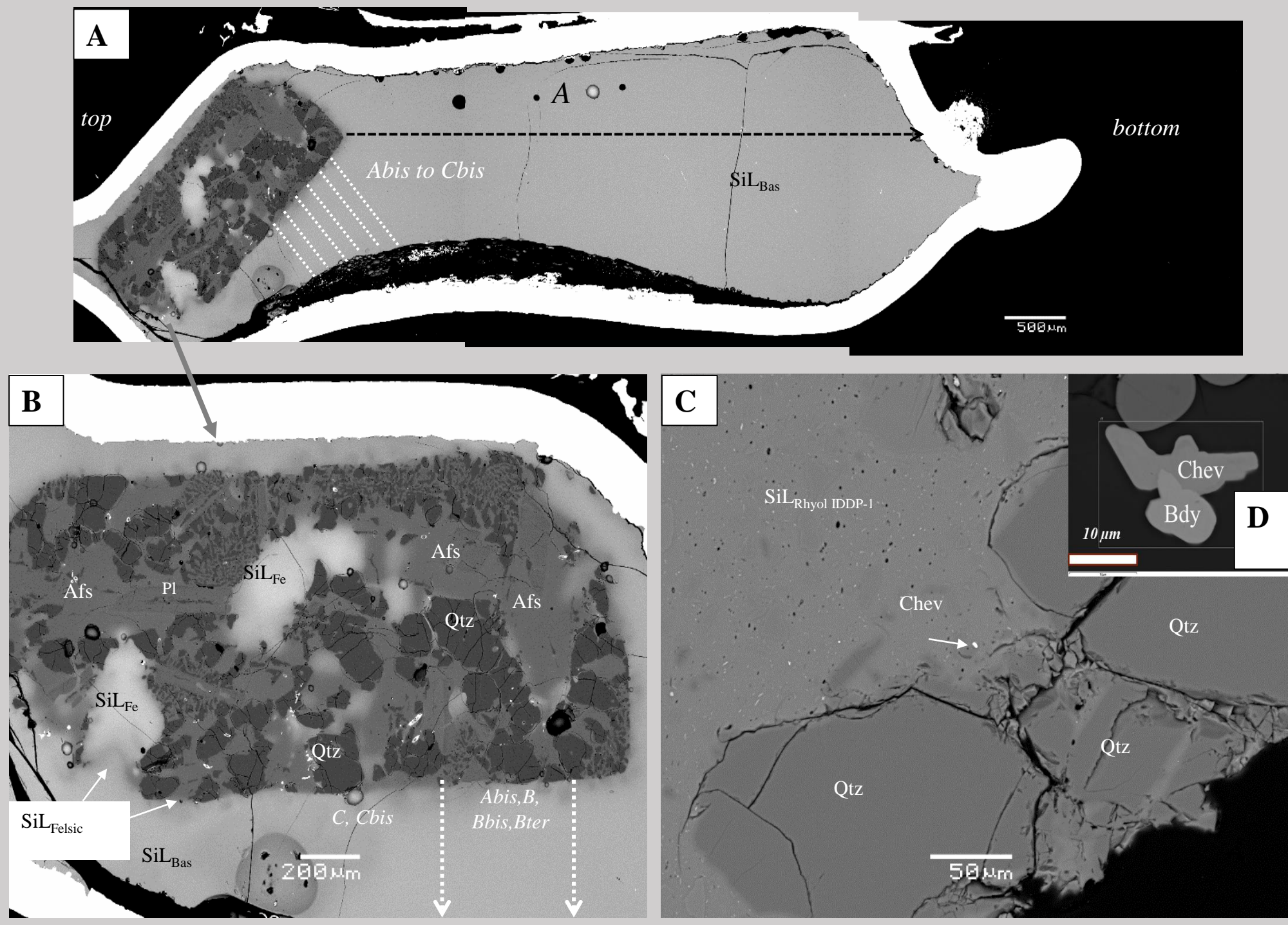


Figure 2. (A) Backscattered electron image of partially melted felsic granophyre (IC-82) in the contact with basaltic glass after the (18) interaction experiment and the measured profiles from A to Cbis. (B) BSE image of partially melted felsic granophyre with the measured parallel profiles (A bis, B, Bbis, Bter, C, Cbis). SIL_{Bas} – basaltic glass; SIL_{Fe} – Fe-rich silicate liquid; SIL_{Felsic} – interface felsic glass; Qtz – quartz; Afs – alkali feldspar and Pl – plagioclase. (C & D) BSE image of natural chevkinite (Chev, Ca-REE silicate) mineral in assemblage with partially dissolved quartz (Qtz) in the natural IDDP-1 glass. SIL_{Rhyol} IDDP-1 – natural rhyolitic glass.

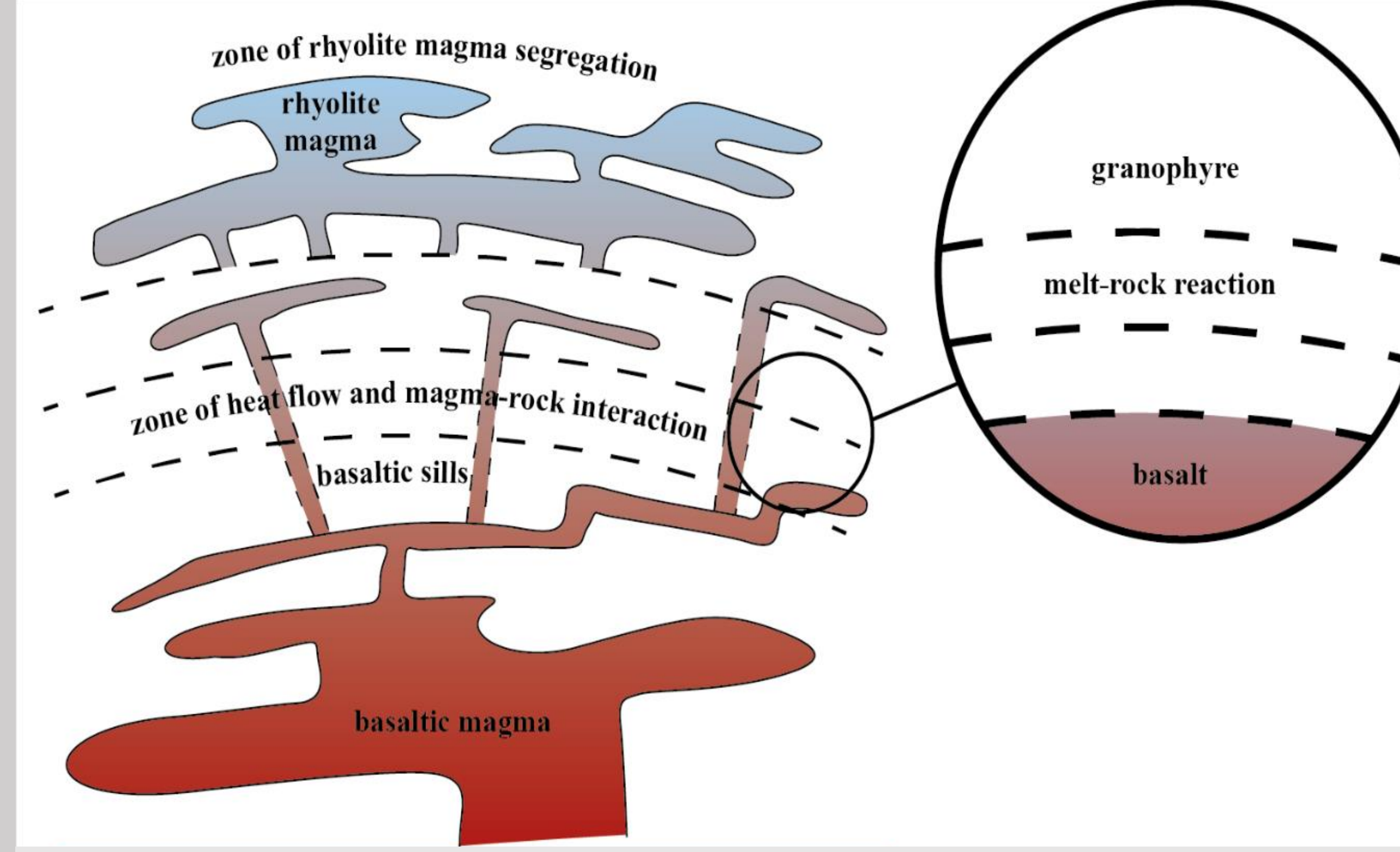


Figure 7. Model of the rhyolite magma genesis in the shallow crust of the Krafla region, Northern Iceland. The intruding sill of the basaltic magma interacts with the host crustal granophyre rock upon the basaltic magma intrusion and emplacement in the hybrid crust. The schema of basaltic magma-felsic rock interaction zone is detailed in the insert on the right. In order to produce the IDDP-1 rhyolite, the parental granophyre rock was shortly intercalated with the super-liquidus basaltic magma in the Krafla caldera setting, and the felsic granophyre rock interacted with basaltic magma. We propose that to produce the natural glasses observed in boreholes KJ-39 and IDDP-1 of Krafla volcano, the parental granophyre rock was progressively melted due to interaction with a hot basaltic magma, allowing the formation of chemically heterogeneous magma, which was sampled in 2008 and 2009, respectively, on the same depths by drilling.

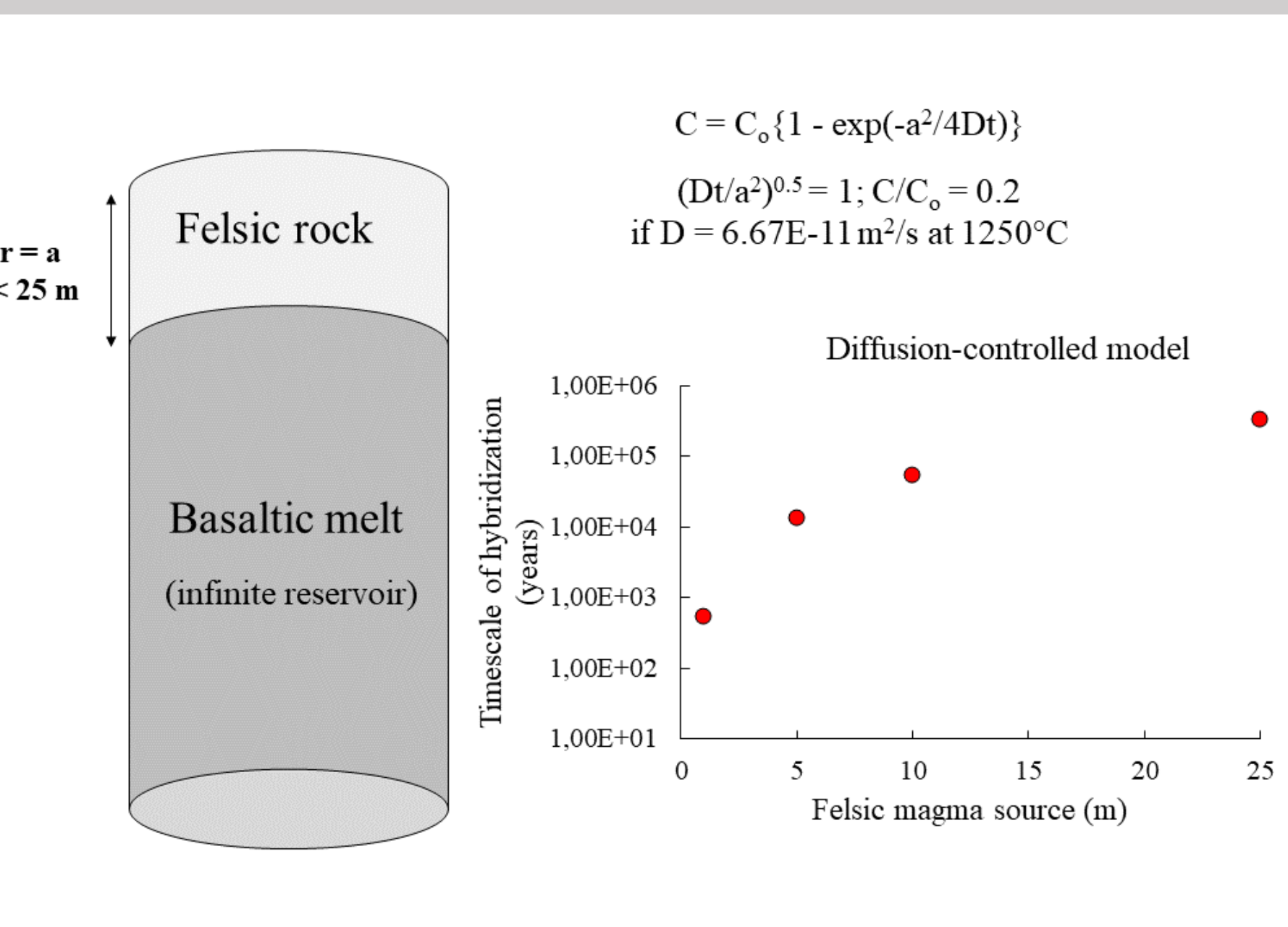


Figure 6. Diffusion-controlled model of hybridization of granophyre rock source in a basaltic reservoir using equation (eq. 1) corresponding to concentration distributions for a cylindrical rock source. The red points correspond to model calculations for the high-temperature regime using diffusion of $D = 6.67\text{E-}11 \text{ m}^2/\text{s}$ at 1250°C.

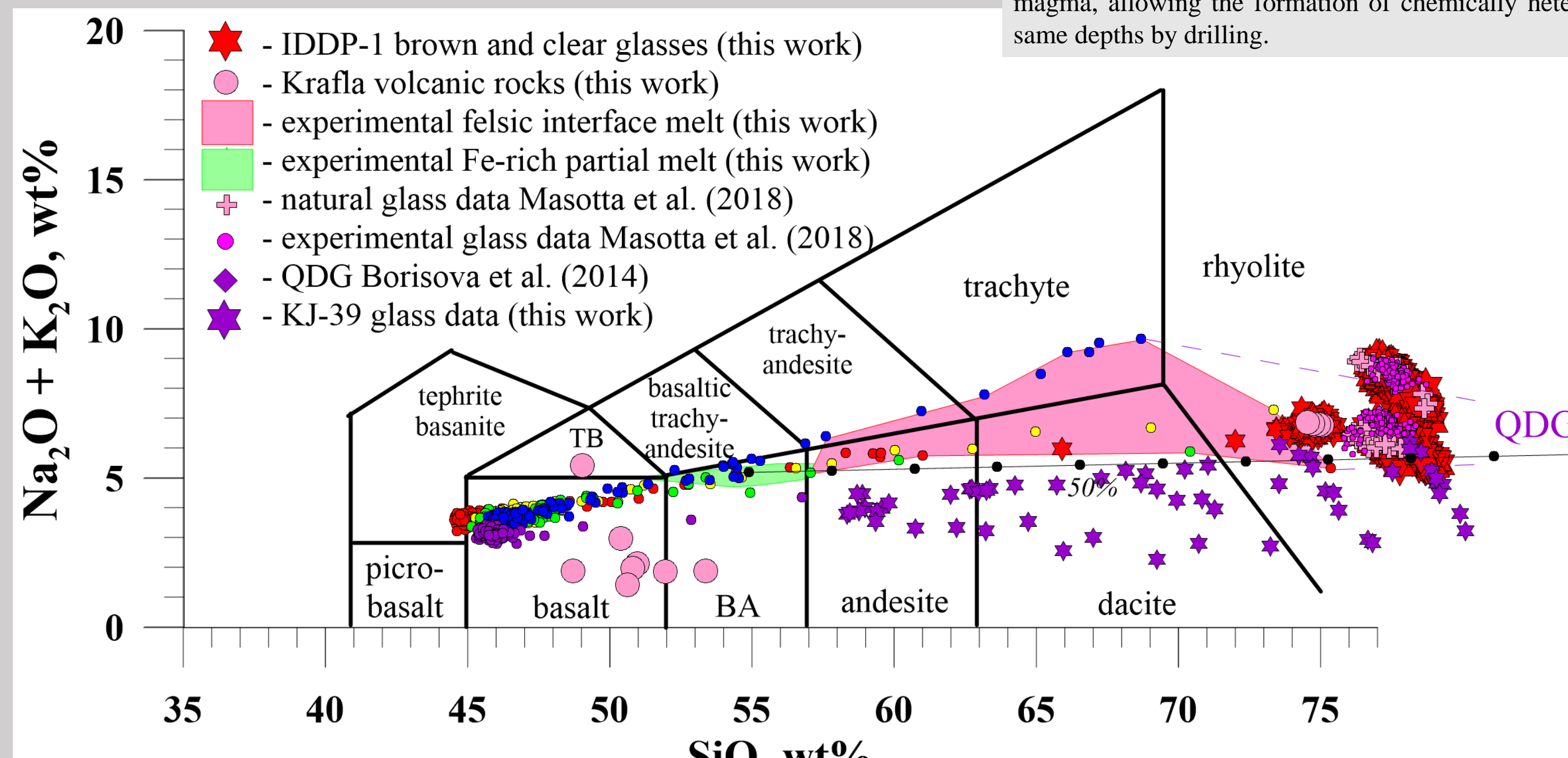


Figure 3. (A) SiO_2 profiles in the basaltic glass from the interface with the partially melted granophyre after the first-design 18 run. (B) Classification diagram after Le Maitre (2003) demonstrating the compositional profiles A to C in comparison to the composition of the IDDP-1 glasses. BA – basaltic andesite; QDG – quartz dissolution glasses with 80 – 85 wt% SiO_2 after Borisova et al. (2014). The experimental felsic interface melt is considered of $>57 \text{ wt}\% \text{ SiO}_2$. The binary mixing line corresponds to mixing between the internal Fe-Ti-rich zones and pure quartz dissolution glasses.

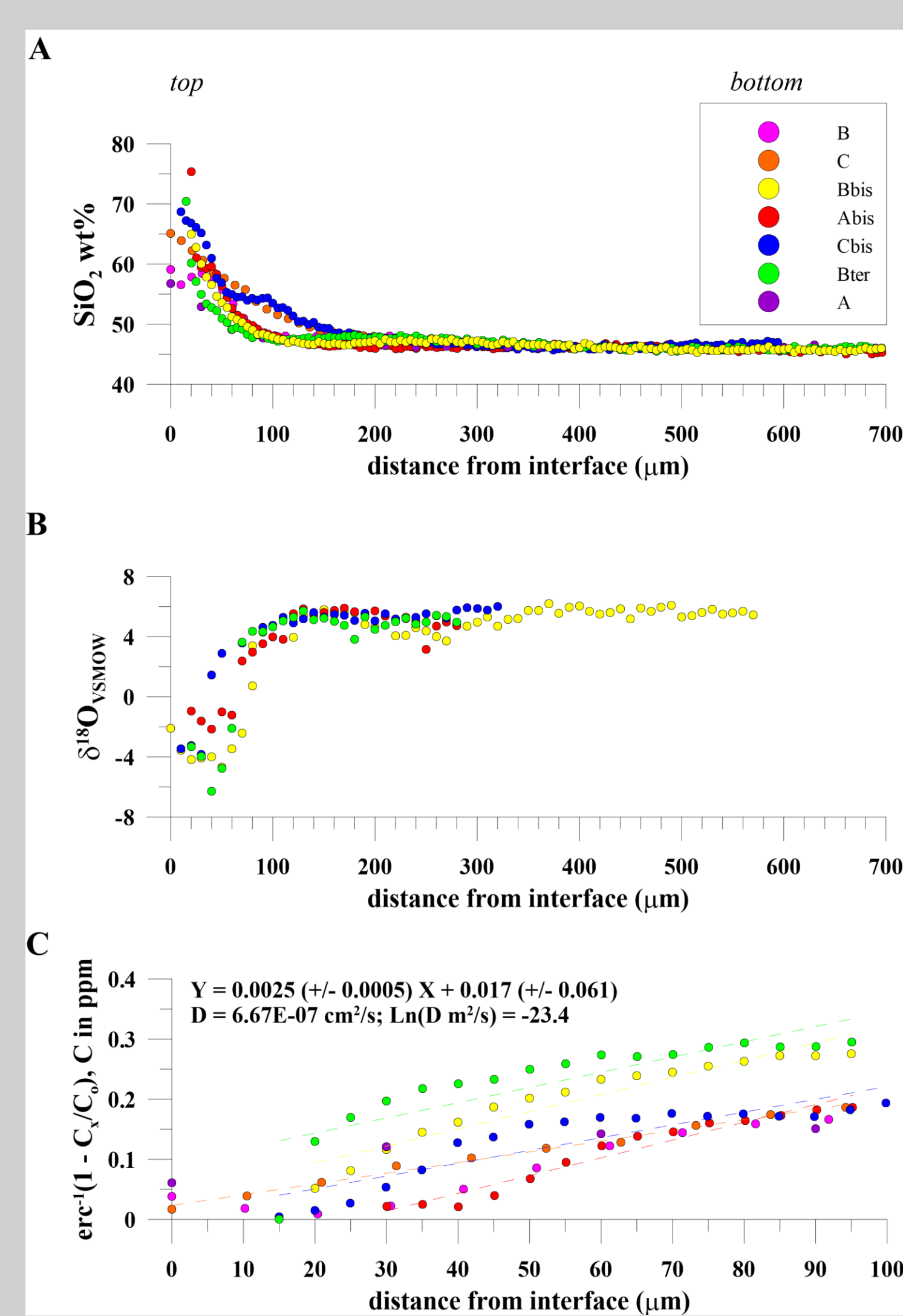


Figure 5. (A) SiO_2 profiles in the glass on the interface with the partially melted granophyre after the first-design 18 run. (B) $\delta^{18}\text{O}_{\text{VSMOW}}$ profiles in the glass on the interface with the partially melted granophyre after the first-design 18 run. (C) Silica profiles expressed in terms of error function of $(\text{erfc}((C_0 - C)/C_0))$, where C_0 is Si concentration (in ppm) in the profile and C_0 is the Si concentration (in ppm) in the interface melt (the first-design 18 run). Several fits suggest the average diffusion of $D = 6.67 \pm 1.15 \times 10^{-7} \text{ cm}^2/\text{s}$ ($6.67 \pm 1.15 \times 10^{-11} \text{ m}^2/\text{s}$), which is similar to effective binary diffusion of silica in anhydrous basaltic melts at 1250°C.

Table 2. Composition of the starting materials, the Krafla basalt and IDDP-1 brown glass and experimental partial and interface glasses produced due to stable configuration experiments

Sample number	Starting Fe-basalt (BAS)	Krafla basalt AB	IC-82**	SIL _{Rhyol} IDDP-1***	Experiment interface SIL _{Felsic} (average)	Experiment partial SIL _{Felsic} (average)
Details:	Fe-Ti basalt	Krafla basalt	Krafla granophyre	rhyolite glass (brown)	SIL _{Felsic} (average)	SIL _{Felsic} (average)
Method:	EPMA/LA-ICP-MS	Bulk-rock chemistry	Bulk-rock chemistry	EPMA/LA-ICP-MS	EPMA	EPMA
				(265 points)	(21 points)	(12 points)
SiO_2	45.91	49.98	74.71	74.65 ± 0.67	63.9 ± 5.2	54.9 ± 1.9
TiO_2	4.58	2.16	0.47	0.33 ± 0.02	1.0 ± 0.7	3.0 ± 0.3
Al_2O_3	12.40	13.21	11.95	11.31 ± 0.15	13.8 ± 3.1	9.0 ± 1.1
FeO	15.00	N.A.	N.A.	2.91 ± 0.11	5.0 ± 2.5	18.2 ± 1.2
Fe_2O_3	N.A.	15.95	3.66	N.A.	N.A.	N.A.
MnO	0.23	0.25	0.08	0.07 ± 0.03	0.08 ± 0.06	0.41 ± 0.05
MgO	4.77	5.15	0.35	0.21 ± 0.03	3.3 ± 1.8	2.7 ± 0.5
CaO	9.87	9.35	1.84	1.47 ± 0.06	4.6 ± 1.8	4.6 ± 0.7
Na_2O	3.33	2.56	4.06	3.86 ± 0.16	4.5 ± 0.5	3.5 ± 0.2
K ₂ O	0.96	0.40	2.65	2.88 ± 0.08	2.4 ± 1.0	1.7 ± 0.1
P ₂ O ₅	0.64	0.21	D.L.	0.05 ± 0.03	0.11 ± 0.09	0.18 ± 0.07
LOI	N.A.	0.04	D.L.	N.A.	N.A.	N.A.
Total	-	-	99.77	97.75 ± 0.78	98.7 ± 0.6	98.2 ± 0.9
Ba ppm	171	104	476	494.87 ±	N.A.	N.A.
Ce	58.2	28.5	80.6	80.62 ± 2.12	N.A.	N.A.
La	24.1	11.9	39.6	38.60 ± 0.96	N.A.	N.A.
Nb	30.0	11.9	29.1	34.94 ± 6.43	N.A.	N.A.
Nd	33.1	18.9	38.5	37.57 ± 1.18	N.A.	N.A.
Rb	17.2	7.54	64.4	73.32 ± 2.49	N.A.	N.A.
Sr	41.2	16.1	72.9	58.65 ± 1.59	N.A.	N.A.
Y	33.6	41.3	61.1	62.33 ± 1.28	N.A.	N.A.
Zn	273	161	74.3	N.A.	N.A.	N.A.
Zr	231	144	425	407.52 ±	N.A.	N.A.
H_2O	0.18	1.22	0.13	1.9 [§]	-	-
CO_2	<0.04	0.11	0.08	N.A.	-	-
S bulk	0.02	0.01	<0.01	N.A.	-	-
$\delta^{18}\text{O}$	5.4 – 5.8 ^{§§}	-5.6 ^{***}	-1.8	3.1 ^{§§§}	-4.0 – 0.2	-2.7 – (-0.8)

** – original data; LOI – loss on ignition; N.A. – not analyzed; D.L. – value below detection limit. *** – EPMA data obtained in this work. § – data from Pope et al. (2013). §§ – data from Sigmarsson et al. (2011). §§§ – data from Hampton et al. (2021). **** – suggested value.

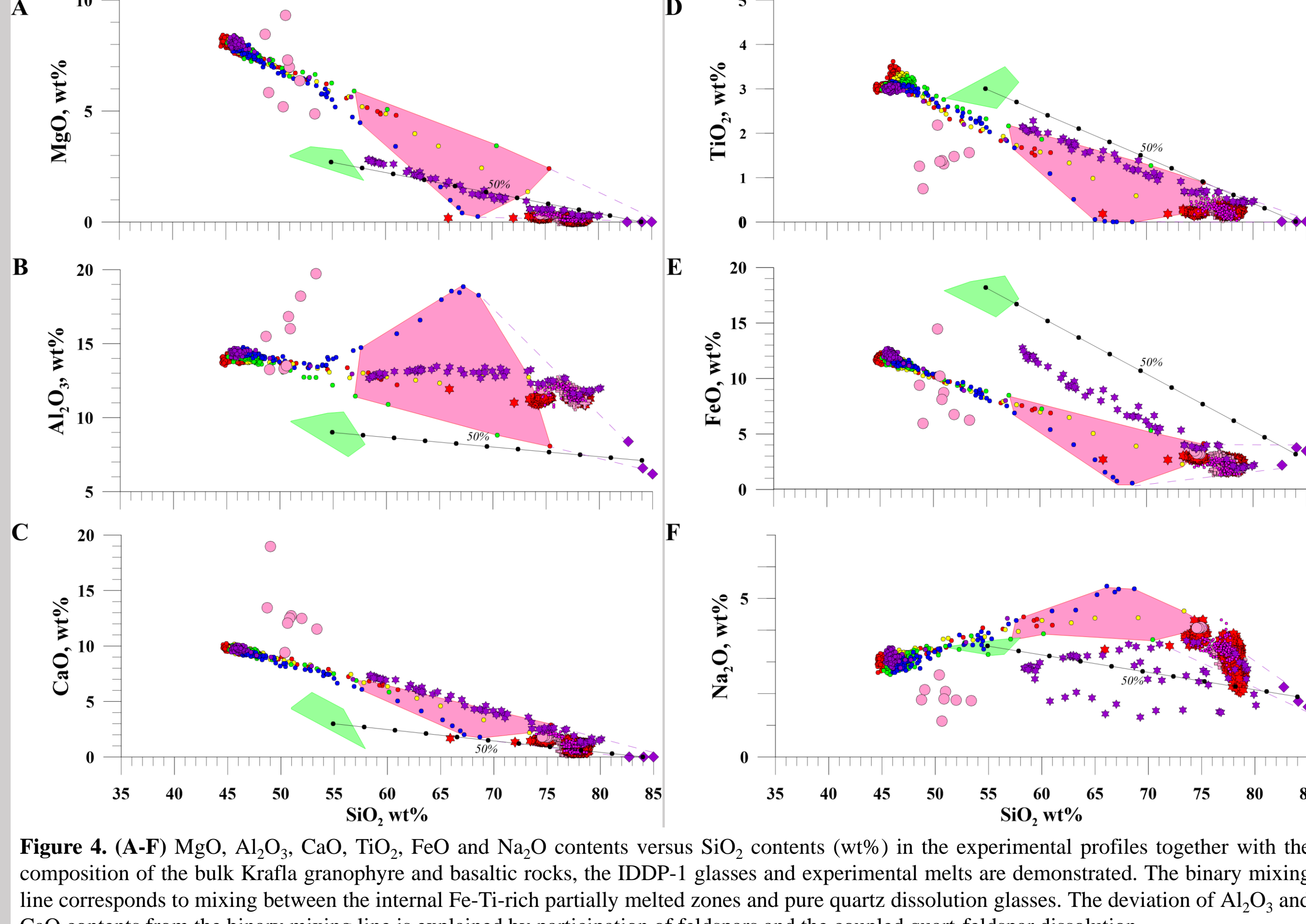


Figure 4. (A-F) MgO , Al_2O_3 , CaO , TiO_2 , FeO and Na_2O contents versus SiO_2 contents (wt%) in the experimental profiles together with the composition of the bulk Krafla granophyre and basaltic rocks, the IDDP-1 glasses and experimental melts are demonstrated. The binary mixing line corresponds to mixing between the internal Fe-Ti-rich partially melted zones and pure quartz dissolution glasses. The deviation of Al_2O_3 and CaO contents from the binary mixing line is explained by participation of feldspars and the coupled quartz-feldspar dissolution.

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