minerals

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Supplementary Material

Top-Down Synthesis of NaP Zeolite from Natural Zeolite for the Higher Removal Efficiency of Cs, Sr, and Ni

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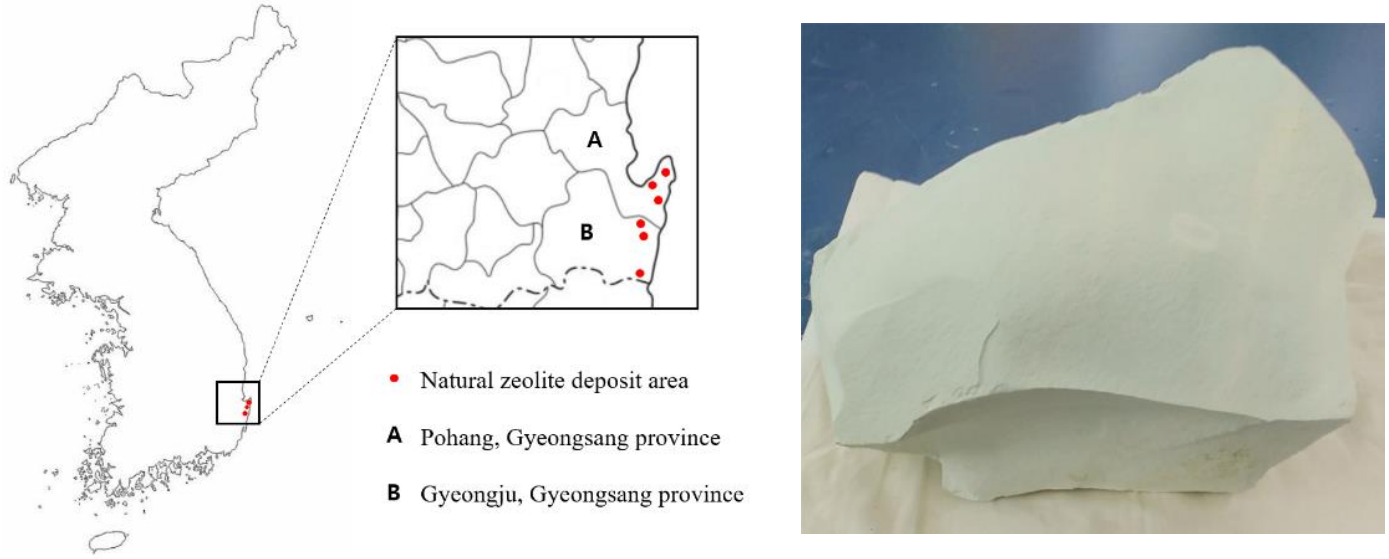

Figure S1. The location of a natural Korean zeolite-mining site (**left**) where the natural zeolite ore sample (**right**) was collected.

Table S1. Composition of Hanbit groundwater.

Composition	Groundwater (ppm)
Na^+	45.9
K^+	2.45
Mg^{2+}	9.76
Ca^{2+}	54.5
Cl^-	28.0
SO_4^{2-}	0.81
NO_3^-	9.4

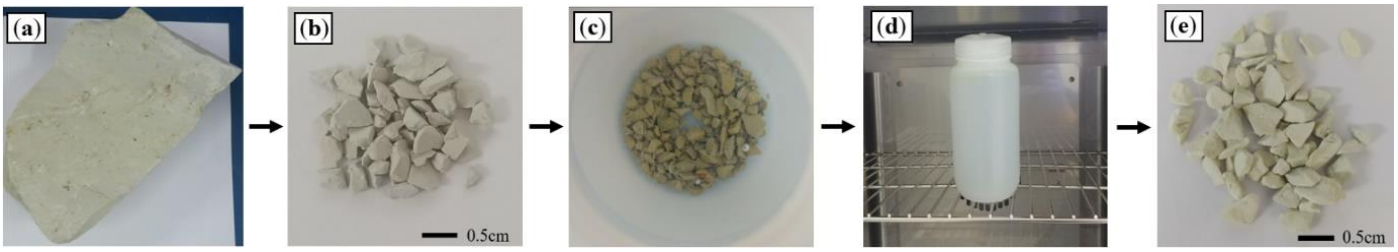

Figure S2. The "top-down" synthesis approach to produce granular-sized zeolites: (**a**) natural zeolite ore, (**b**) crushed natural zeolite (granular-sized), (**c**) zeolite immersed in NaOH solution, and (**d**) during the reaction process in the oven, and (e) resulting as-synthesized NaP zeolite (granular-sized).

Table S2. Chemical compositions of granular-sized natural and NaP zeolites expressed in wt.%.

Compound	Natural Zeolite	NaP Zeolite
SiO_2	72.43	48.70
Al_2O_3	14.10	23.61
Na_2O	3.51	14.8
K_2O	2.36	1.17
CaO	2.08	3.41
MgO	0.81	1.37
Others	3.81	6.94

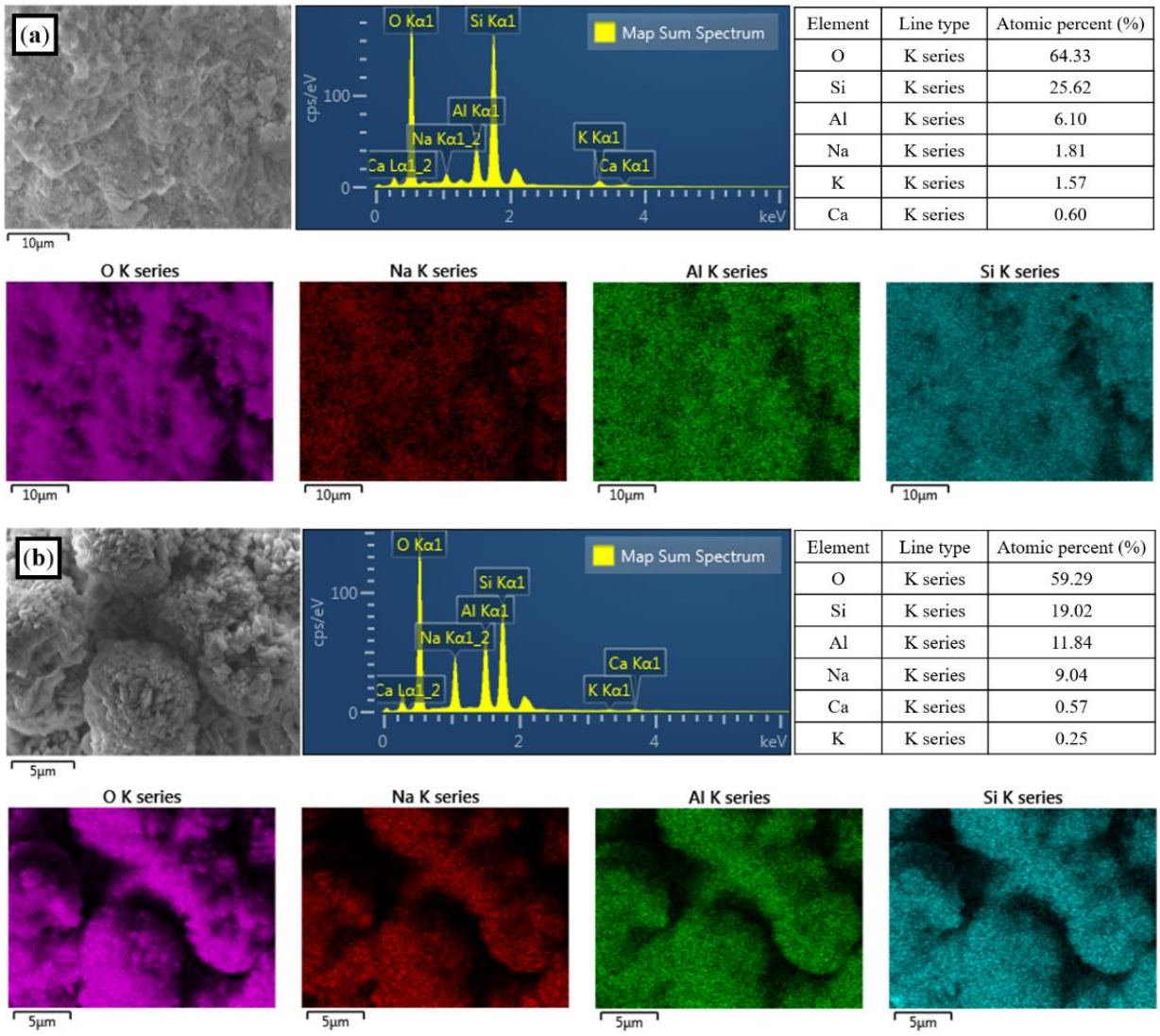

Figure S3. Elemental mapping of natural zeolite (**a**) and NaP zeolite (**b**) with SEM-EDX analysis.

Table S3. Textural parameters of natural and NaP zeolites.

	Natural Zeolite (powder-sized)	NaP Zeolite (powder-sized)	Natural Zeolite (granular-sized)	NaP Zeolite (granular-sized)
Specific surface area (S_{BET}) (m^2/g)	34.446	89.298	31.349	95.949
Total pore volume (cm^3/g)	0.122	0.139	0.077	0.099
Micropore volume (cm^3/g)	0.016	0.036	0.016	0.021

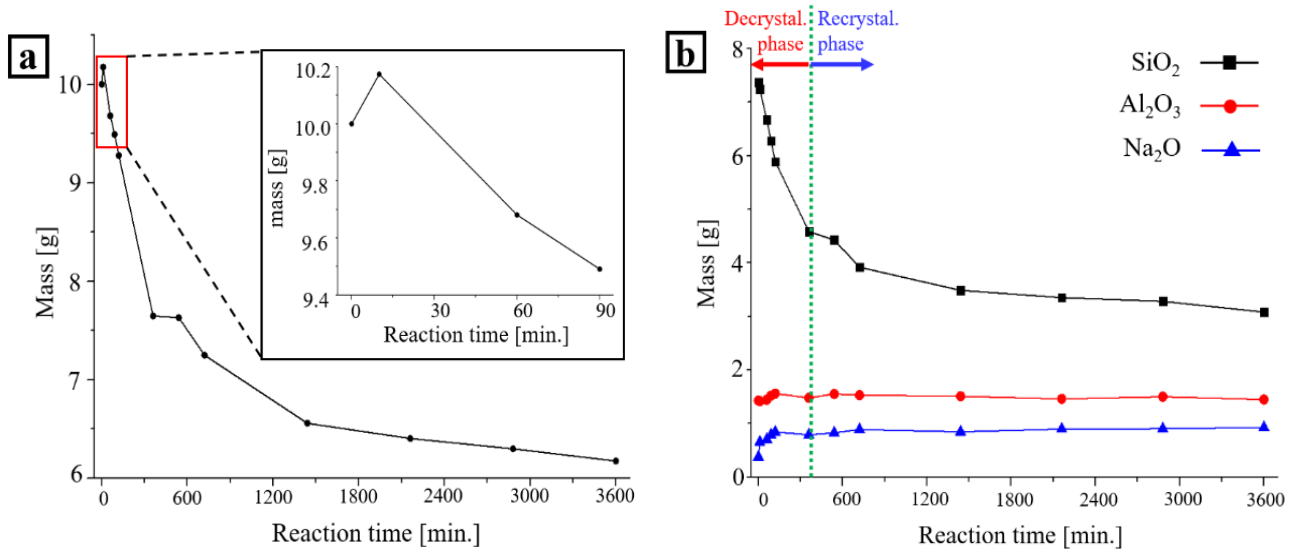

Figure S4. Mass variation (**a**) and composition variation (**b**) of zeolite with different reaction times.

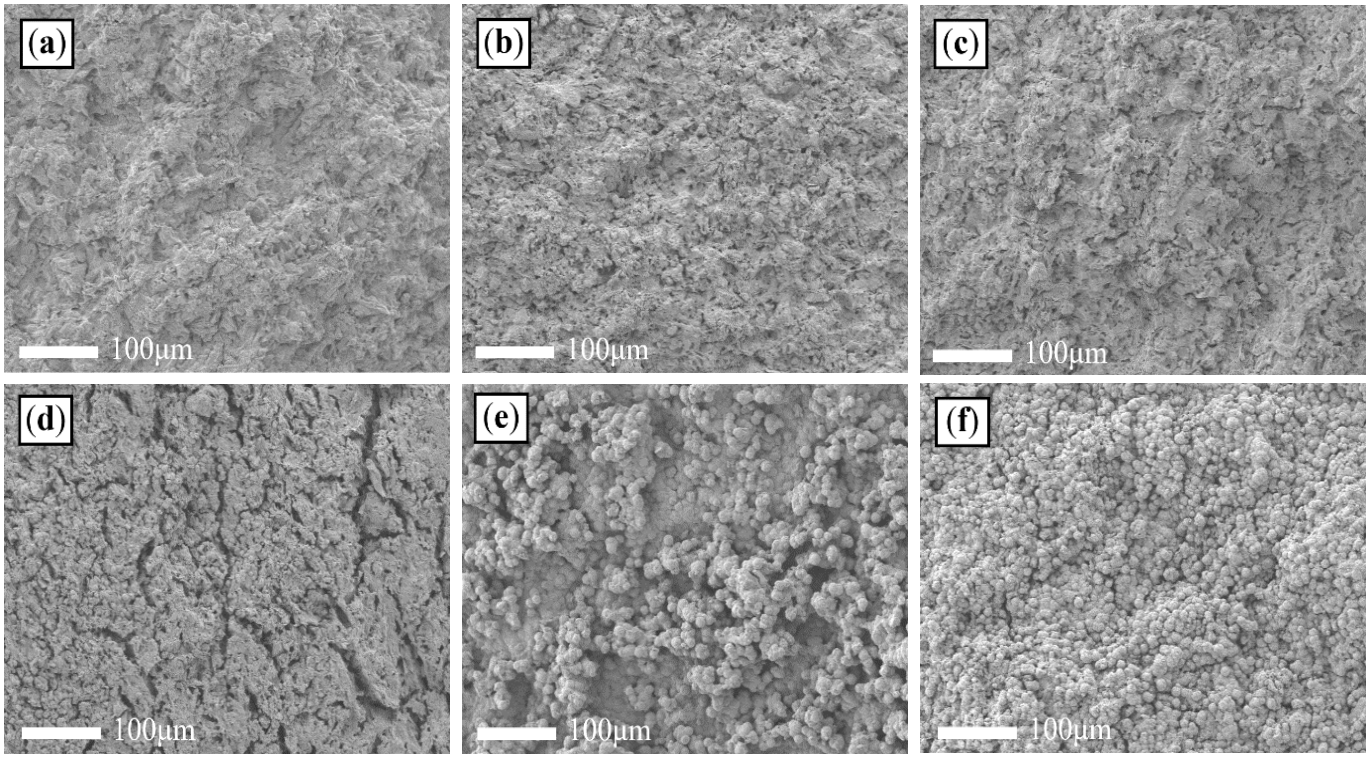

Figure S5. SEM images showing morphological changes at different reaction times; (**a**) 10 min, (**b**) 1 h, (**c**) 2 h, (**d**) 9 h, (**e**), 24 h, and (**f**) 48 h.

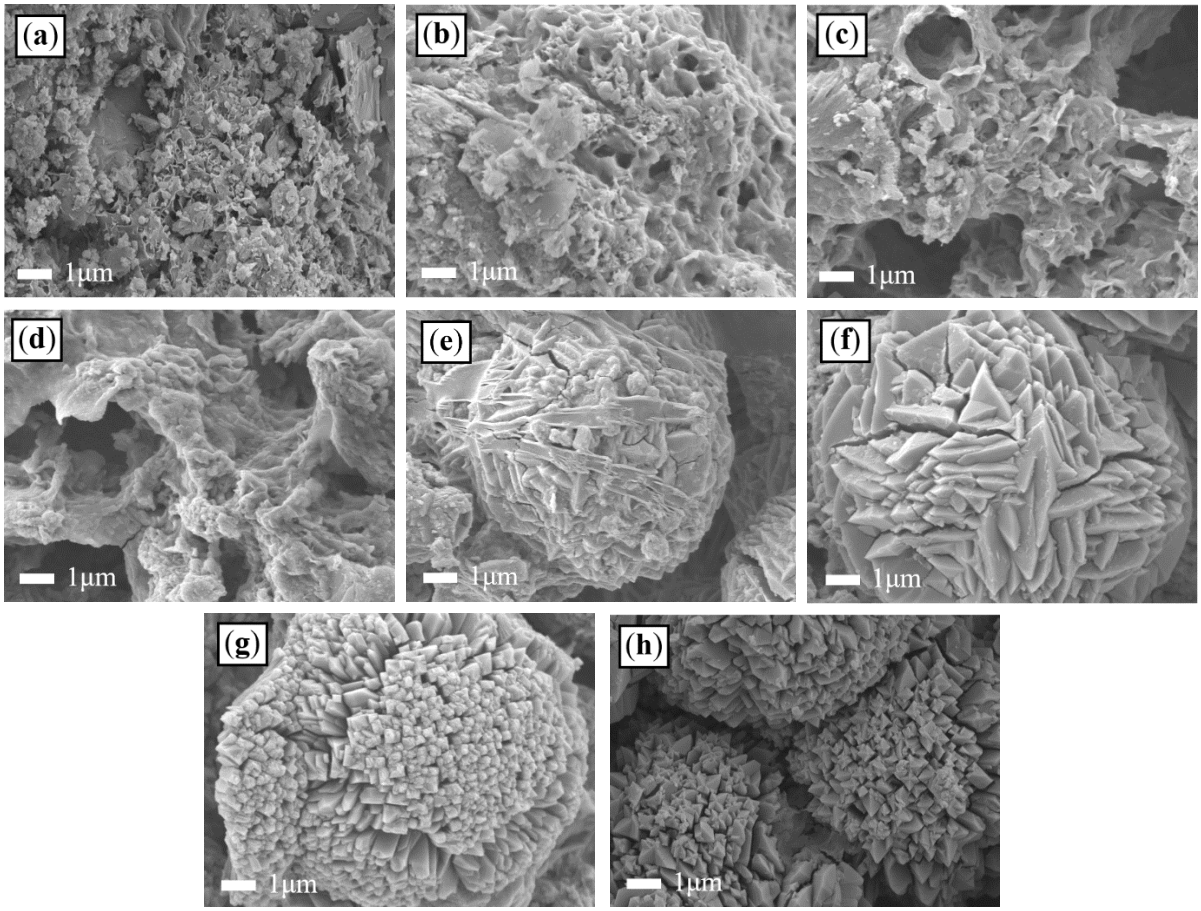

Figure S6. SEM images showing morphological changes at different reaction times; (**a**) Natural zeolite, (**b**) 10 min, (**c**) 1 h, (**d**) 2 h, (**e**) 9 h, (**f**) 24 h, (**g**) 48 h, and (**h**) 60 h.

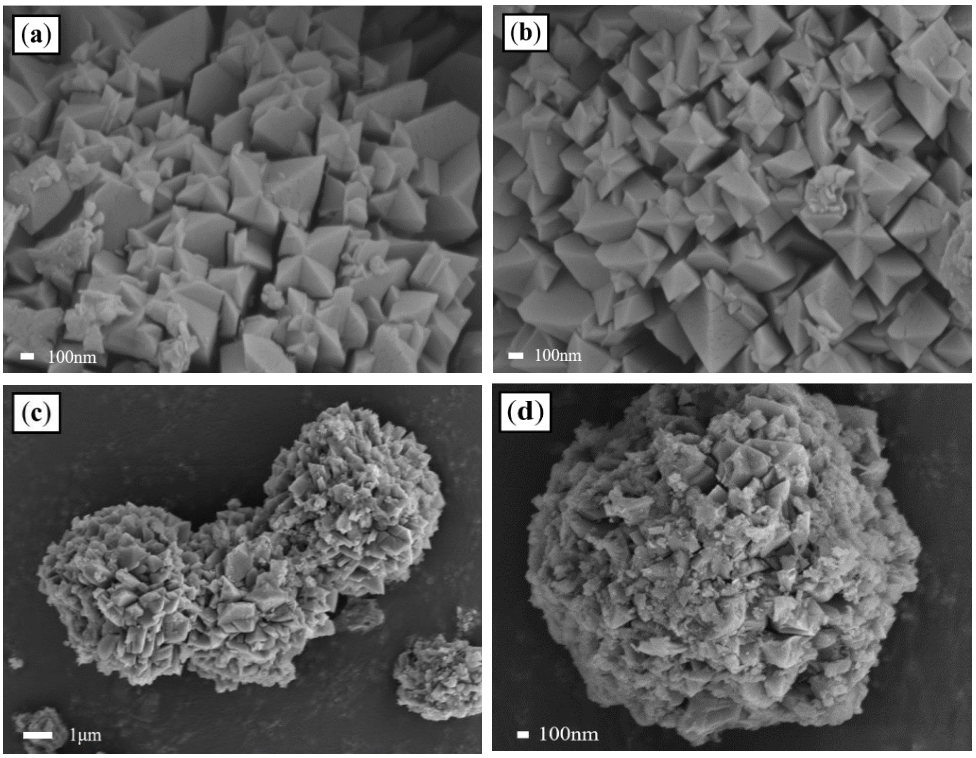

Figure 7. SEM images of two different-sized NaP zeolites (**a**), (**b**): Granular-sized NaP zeolite's surface, (**c**), (**d**): Powder-sized NaP zeolite's surface**.**

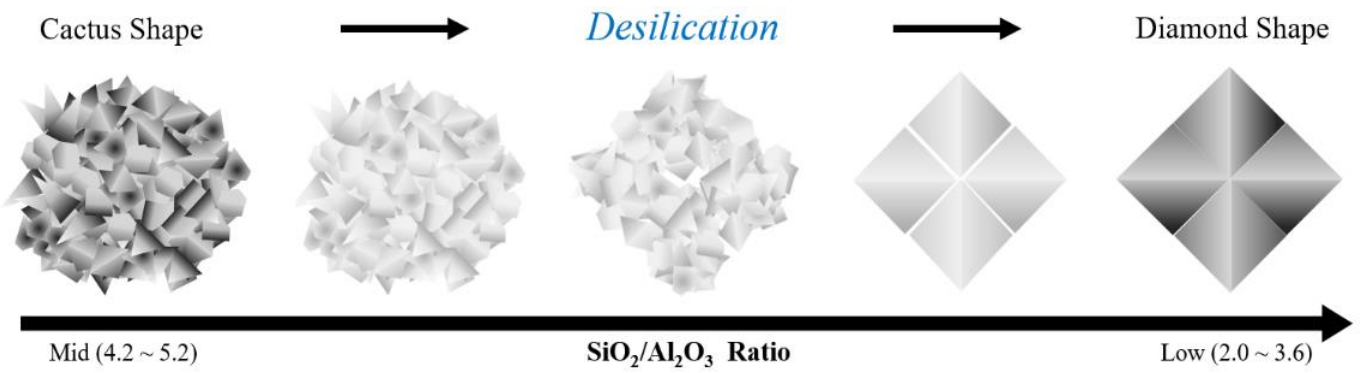

Figure S8. Morphological transition of the NaP zeolite with different Si/Al ratios.

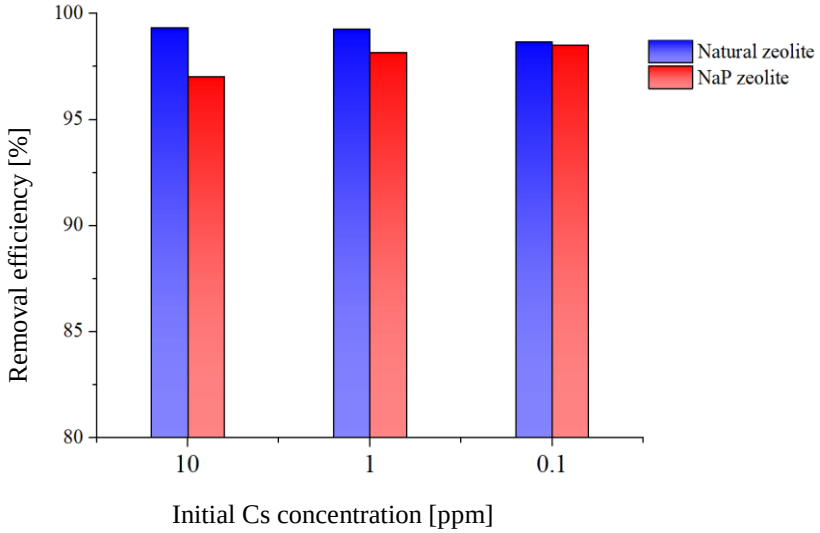

Figure S9. Batch sorption measurements for the removal of Cs at various concentrations in groundwater collected around the Hanbit NPP site. (Note: Error bars were omitted because of size constraints. The initial Cs^+ concentrations were set to 10, 1, and 0.1 ppm, with the solid-to-solution ratio at 100 mL/g.