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Inherited control of crystal surface reactivity

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Abstract: Material and environmental sciences have a keen interest in the correct prediction of material release as a result of fluid-solid interaction. For crystalline materials, surface reactivity exerts fundamental control on dissolution reactions; however, it is continuously changing during reactions and governs the dynamics of porosity evolution. Thus, surface area and topography data are required as input parameters in reactive transport models that deal with challenges such as corrosion, CO₂ sequestration, and extraction of thermal energy. Consequently, the analysis of surface reaction kinetics and material release is a key to understanding the evolution of dissolution-driven surface roughness and topography. Kinetic Monte Carlo (KMC) methods simulate such dynamic systems. Here we apply these techniques to study the evolution of reaction rates and surface topography in crystalline materials. The model system consists of domains with alternating reactivity, implemented by low vs. high defect densities.

Our results indicate complex and dynamic feedbacks between domains of high versus low defect density, with the latter apparently limiting the overall dissolution rate of the former - a limitation that prevails even after their disappearance. We introduce the concept of “inherited” control, consistent with our observation that maximum dissolution rates in high defect density domains are lower than they would be in the absence of low defect density neighboring domains.

The controlling factor is the spatial pattern of surface accessibility of fluids. Thus, the distribution of large etch pits centers is inherited almost independently of spatial contrasts in crystal defect density during ongoing reactions. As a critical consequence, the prediction of both the material flux from the reacting surface and the evolution of topography patterns in crystalline material is constrained by the

30 reaction history. Important applications include the controlled inhibition of reactivity of crystalline
31 materials as well as the quantitative evaluation and prediction of material failure in corrosive
32 environments.

33 **Keywords:** Kinetic Monte Carlo simulation, rate spectra, crystal dissolution, surface reactivity, surface
34 topography and roughness patterns

35

36 **1 Introduction**

37 Crystal defects cause the formation of etch pits during dissolution and corrosion processes. A large
38 body of literature exists about this process, ranging from BCF theory to the stepwave model (e.g., Casey
39 et al., 1988; Cheng, 1993; Dove et al., 2005; Lasaga and Lutge, 2001; Lutge et al., 2013; Tang et al.,
40 2003). The growth and coalescence of etch pits controls the evolution of reacting rough surfaces and
41 pore walls and affects thus porosity in natural and technical materials. Examples include the formation
42 of secondary porosity in reservoirs (Taylor et al., 2010) or the impact of microstructures on corrosion
43 (Horlait et al., 2014). As a consequence, small-scale approaches for modeling pore-scale reaction
44 processes are gaining increased interest (Iliev et al., 2015; Steefel et al., 2015). The evolution of porosity
45 alters the fluid-solid interface and, thus, the effective reactivity of the dissolving material (Daval et al.,
46 2013; Dele-Afolabi et al.; Dong et al., 2011; Fischer et al., 2014; Xu et al., 2016). By changing the
47 surface roughness and topography of the reacting pore walls and throats (Anbeek, 1992), the evolution
48 of new void volumes constrains via permeability alternations both the diffusive and advective transport
49 of dissolved material and thus impacts reactive flow conditions (Anovitz and Cole, 2015; Gao et al.,
50 2017; Iliev et al., 2015; Mostaghimi et al., 2016). Moreover, coupled dissolution–precipitation reactions
51 rely on the formation of voids as initial pore volumes as this allows the fluid to maintain contact with
52 the reacting interfaces (Chen et al., 2014). Accordingly, the quantitative predictability of porosity
53 evolution during fluid-solid interaction is of great interest in multiple disciplines of material and
54 environmental sciences, and the development of appropriate tools is at the forefront of fundamental and
55 applied research (Steefel et al., 2015; Yang et al., 2015). The formation of void volumes significantly
56 influences the efficiency of fluid-solid interactions by affecting the rate of solute transport. Related
57 data are required as input parameters in reactive transport models dealing with questions such as CO₂

58 sequestration (Hellevang et al., 2013; Monger et al., 2015), extraction of thermal energy (Dillinger et
59 al., 2014), as well as waste management in rock formations (Kim et al., 2011).

60 Crystal surface reactivity is an important but variable boundary condition that constrains the evolution
61 of porosity. The defect density variability in crystalline materials is a critical parameter that defines
62 spatial domains of contrasting reactivity (Hiemstra and van Riemsdijk, 1999). The accessibility of
63 domains with constant or contrasting surface reactivity does change continuously over reaction time.
64 Thus, changing surface-energetic complexity does superimpose the changing geometric complexity. As
65 a consequence, the boundary conditions of the reacting system change dynamically. The analysis of
66 such a system with multiple changing input parameters is a classic task for a modelling approach.
67 Kinetic Monte Carlo (KMC) simulation calculations offer a large enough length scale to address this
68 problem appropriately (Lasaga and Blum, 1986).

69 As a starting point, we study the evolution of reaction rates and surface topography pattern in a simple
70 *Kossel* crystal (Kossel, 1927; Stranski, 1928) by utilizing KMC simulation techniques. More
71 specifically, the model material is built up of domains of constant activation energies but having varying
72 defect densities in order to provide well-defined variations in the surface reactivity (Liu et al., 2017;
73 Liu et al., 2015; Luttge et al., 2013). We apply the rate spectra concept to KMC results in order to
74 analyze systematically the rate contributors in the frequency domain of rate datasets (Fischer et al.,
75 2012; Fischer et al., 2014). Using this concept, the identification of both invariance or temporal
76 variability of such rate contributors over reaction time provides quantitative insight into the overall
77 reaction rates of crystalline materials (Fischer and Luttge, 2017; Michaelis et al., 2017; Saldi et al.,
78 2017).

79 In detail this study addresses the following questions: (1) How variable are reaction rates during
80 dissolution of multiple domains or grains of crystalline material with variable defect density? Do such
81 domains provide constraints to the effective surface reactivity? (2) How variable are the resulting pore
82 volume and etch pit distribution? What parameters govern the initial formation of topography patterns
83 in crystalline material? Is there any predictive power associated with such a parameter? (3) To what
84 extent is reactivity inherited in crystalline material? Are low-reactivity domains able to slow down the
85 overall reaction rate significantly with consequences such as reduction in surface reactivity?

86

87 **2 Methods**

88 **2.1 Kinetic Monte Carlo simulations**

89 A Kinetic Monte Carlo (KMC) program simulates a series of single reactions at the atomic scale. Here,
90 we apply a KMC model for a *Kossel* crystal (Kossel, 1927). A Kossel crystal consists of a cubic lattice
91 composed of a single chemical species. The bond energies Φ between all atoms are constant. The KMC
92 model is based on the Bortz-Kalos-Lebowitz (BKL) algorithm (Bortz et al., 1975). The algorithm allows
93 for a reactive event at each iteration step. The simulation provides the temporal evolution of a dissolving
94 surface, based on a series of single reaction events on the crystal surface. Lasaga and Luttge (2004)
95 provide detailed and general information about KMC models for mineral dissolution. In this study, the
96 model simulates dissolution reactions under conditions far from equilibrium.

97 KMC models are now routinely used for studying surface site-specific reaction kinetics (e.g., Cama et
98 al., 2010; Kerisit et al., 2008; Kurganskaya and Luttge, 2016; Meakin and Rosso, 2008). Implemented
99 parameters in KMC algorithms include the lattice resistance effect or the network of surface hydrogen
100 bonds. An increasing number of ab initio calculations provides the critical parameters for the probability
101 equations. Thus, the reactivity of solid materials without defects is properly implemented in KMC
102 approaches. In this study, we focus on the impact of varying defect densities in crystals. The reported
103 variability in natural and technical crystalline material is huge and includes several orders of magnitude
104 (Blum and Lasaga, 1987), similar to the ranges utilized in this study (**Table 1**).

105 We utilize periodic boundary conditions to eliminate the influence of model size in (x,y) direction. In
106 order to investigate material domains of varying reactivity, we apply a “layered cake” model of a solid,
107 composed of layers with variable thickness and defect densities. The type of crystal defects in this study
108 are screw dislocations. Screw dislocations form an initial structure during the dissolution process, i.e.,
109 the hollow core. Ongoing dissolution results in the formation of etch pits along the hollow core. Our
110 model has well-defined input parameters, i.e., the number of layers, layer thickness, and defect density
111 (**Table 1**). Defects are randomly seeded in each layer by using uniformly distributed random numbers
112 for (x,y) core center positions. The defect length is identical to the domain thickness.

113

Table 1: KMC simulation parameters for the dissolution of KOSSEL crystals with a lattice constant of 0.2 nm. Several KMC runs utilized crystals that are built-up of several domains in z-direction (domain thickness) that are characterized by alternating defect densities. In this case, a structure starting with a high (*h*) reactivity domain followed by a low (*l*) reactivity domain was analyzed and vice versa, e.g., *hlhl* & *lhhl*, see **Fig. 2**.

Simulation results in	system size (area)	domain thickness	defects/ domain	number of domains	dissolved atoms	number of runs
Fig. 1	50×50 nm ²	10 nm	50	1	1E+06	1
Figs. 2, 3	300×300 nm ²	1 nm	1000 (<i>h</i>) 10 (<i>l</i>)	4	1E+06	2
Fig. 3C	300×300 nm ²	10 nm	1000	1	1E+06	1
			100	1	1E+06	1
			10	1	1E+06	1
Figs. 4, 5	300×300 nm ²	10 nm	150 (<i>h</i>) 15 (<i>l</i>)	2	10E+06	2
Fig. 6	300×300 nm ²	2 nm	100 (<i>h</i>) 10 (<i>l</i>)	10	6E+06	2
Fig. 7	300×300 nm ²	20 nm	100 (<i>l</i>)	1	6E+06	1
		2.0 nm	100 vs. 10	10		
		2.2 nm	110 vs. 11	10		
		4.0 nm	200 vs. 20	10		
		20 nm	1000 (<i>h</i>)	1		

114

115 The simulation starts with the opening of hollow cores in the top layer. As soon as the dissolving layer
 116 exposes a defect outcrop in the subjacent layer, a hollow core opens and a new etch pit evolves (Burton
 117 et al., 1951; Lasaga and Lutge, 2001). KMC runs were performed under constant bond strength
 118 conditions ($\Phi = 4$, normalized to kT units). The dissolution probability P_i of an atom with i bonds is

$$119 \quad P_i = e^{\left(\frac{-\Phi}{kT}\right)} \quad (1)$$

120 Multiple types of reactive domains were used in layered cake models. We investigated the impact of
 121 defect density and domain thickness in different KMC simulation calculations, details about the
 122 parameter variation of the crystals are summarized in **Table 1**. We varied the starting conditions of the
 123 model, i.e., the reactivity of the uppermost layer was either (*h*) or (*l*).

124

125 2.2 Reaction rate analysis: rate maps and rate spectra

126 Rate maps are calculated using the formula:

$$127 \quad R(x, y, t_i) = \frac{h(x, y, t_{i-1}) - h(x, y, t_i)}{t_i - t_{i-1}} = \frac{\Delta h_i(x, y)}{\Delta t_i} \quad (2)$$

128

129

130 $R(x,y,t)$ is the local dissolution rate for a single node, defined by (x,y) coordinates, and i is the time
131 step. Such rates reflect the increase (growth) or decrease (dissolution) of the initial height h of a given
132 point (x,y) during a time interval $(t_i - t_{i-1})$. The frequency distribution of the R values forms a rate
133 spectrum (Fischer et al., 2012). The simulations output the surface height maps at fixed iteration steps,
134 the distributions of the reactive sites, and the overall material flux as a function of time. The iteration
135 steps are defined by the number of dissolved blocks. The reaction time increment, Δt_i , between the
136 events $i - 1$ and i , is calculated as a reciprocal sum of the number N of probabilities P of surface
137 reactions normalized by the reaction attempt frequency, ν (Blum and Lasaga, 1987), i.e., the
138 fundamental frequency (Pelmenschikov et al., 2001), that we set to 10^{12} [s^{-1}]:

$$139 \quad \Delta t_i = \frac{1}{\nu \sum_{j=1}^N P_j} \quad (3)$$

140 This permits the tracking of the reaction progress and to analyze kinetic parameters such as overall rate,
141 kink and step site densities in time units (TU, see below). The applied fundamental frequency number
142 is in the order of magnitude of the intermolecular vibrational frequency of bulk water (Walrafen, 1972).
143 The frequency of the reaction attempts is similar to this frequency because the dissolution process is
144 water-catalyzed (Pelmenschikov et al., 2001). Consequently, bond strengths are utilized for probability
145 calculations.

146

147 **3 Results and discussion**

148 **3.1 Quantitative analysis of surface reaction rates**

149 Material flux maps provide information about the spatial distribution of heterogeneous material flux.

150 Flux maps of KMC calculation results offer the opportunity to analyze the mechanistic connection

151 between crystal surface reactions and material flux at any time step. **Figure 1** exemplifies how this

152 analysis reveals information about material flux characteristics.

153 Based on KMC results, a model for crystal dissolution via the stepwave movement mechanism has been

154 introduced (Lasaga and Lutge, 2001). According to this model, crystal dissolution is controlled by

155 stepwaves emanating from dislocation cores (**Fig. 1A; B**). The evolution of superimposing stepwaves

156 and their efficiency in terms of material removal is quantitatively illustrated by using material flux maps

157 (**Fig. 1C**) and the corresponding rate components (**Fig. 1D**).

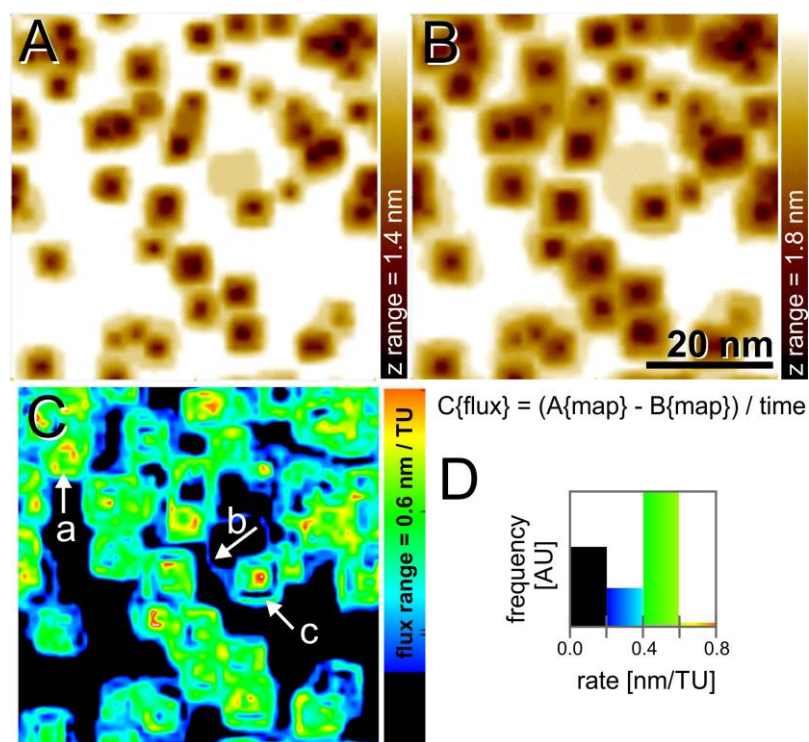


Figure 1: Visualization of results of a Kinetic Monte Carlo dissolution experiment using a *KOSSEL* crystal structure. (A, B) Topography with etch pits after removal of 100'000 and 200'000 blocks. (C) Material flux map shows inert (black) and reactive surface sections related to surface rates. Note the distribution and shape of reactive surface portions: a. highly reactive etch pit wall sections (yellow/red), b. single stepwave of an extinct screw dislocation, c. flux distribution related to complex stepwave structure with change of surface reactivity at an etch pit wall. (D) Rate spectrum of rate map (C) showing the dominant frequency (green color) of rate contributions owing to dissolution stepwaves.

158 As an example, large single stepwaves from inactive screw dislocations (at the height of screw bottoms)
 159 represent low material fluxes. Superimposition of stepwaves from multiple generators results in flux
 160 map sections that illustrate a complex pattern of high vs. low material flux distribution.
 161

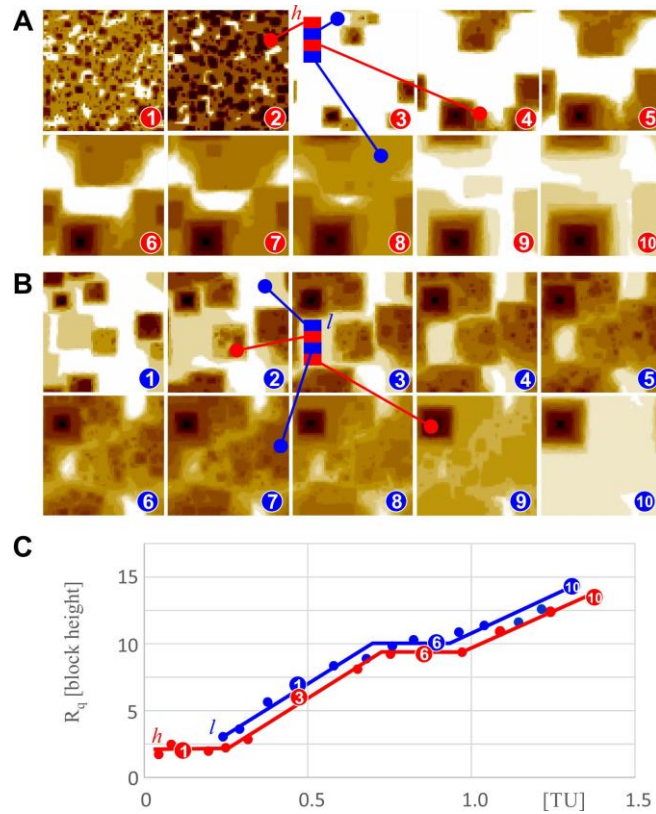


Figure 2: (A) Surface topography evolution of a KOSSEL crystal that consists of four layered domains having alternating defect densities, starting with a high defect density (1000 defects/domain), followed by a low defect density (10 defects/domain). (B) Topography evolution similar to (A), but starting with a low defect density (10 defects/domain), followed by a high defect density (1000 defects/domain). The column sketches in (A) and (B) illustrate the impact of the contrasting defect densities (low (l): blue; high (h): red) on etch pit size and number. (C) Evolution of RMS roughness R_q of both materials (A) and (B). Map size = $300 \times 300 \text{ nm}^2$. Note the difference in reaction time compared to the dissolution of an identical number of surface blocks, e.g. (1)-red vs. (1)-blue due to initial differences in surface reactivity (see A, B).

162

163 3.2 Reactivity of layered crystals with domains having varying defect densities

164 We compare the dissolution rates of KOSSEL crystals that are composed of domains of contrasting
 165 screw defect densities. We vary the initial conditions with respect to the defect density of the uppermost
 166 crystal domain, i.e., high (h) vs. low (l) reactivity (Table 1). Figure 2 illustrates the evolution of the
 167 surface topography and roughness (Fig. 2 A: h , B: l). As expected, the initial topographic contrast of
 168 the surface maps of both crystals is caused by the defect density (Anbeek et al., 1994). A high defect

169 density results in the formation of multiple etch pits having a small lateral extension (**Fig. 2A**, 1-2), a
170 low defect density results in the formation of a few pits with large lateral size (**Fig. 2B**, 1). Subsequently,
171 the dissolution of the subjacent crystal domain leads to the superimposition of small and large etch pits,
172 according to the defect density of the newly-exposed crystal domains. However, the roughness
173 evolution (**Fig. 2C**) is dominated by the topography of large and deep etch pits. The change in-between
174 low- vs. high-reactivity has no clear equivalent in the topography evolution. The reason is that the
175 evolution and growth of a few large pits is a dominant factor of the overall evolution of surface
176 topography. Consequently, the RMS roughness (Thomas, 1999) increases over the total reaction time.
177 **Figure 3** shows the rate maps of the dissolving crystalline material. **Figure 3A** illustrates the locally
178 low rates associated with the dissolution of material having a high defect density (**Fig. 3A**, [1-2], blue
179 color). The growth of etch pits within crystal domains with low defect densities results in locally
180 enhanced reaction rates (**Fig. 3A**, [4], green color). The existence of steep etch pit walls (**Fig. 2**) dictates
181 the further evolution of surface rates and topography, i.e., the increase in spatial heterogeneity of
182 material flux from the surface. A similar evolution is observed for crystal domains with an inverse order
183 of defect density (**Fig. 3B**). The initial contrast in surface rates of high vs. low defect density domains
184 is clearly visible in **Fig. 3C**, sections [1-2] of both h and l domains. The large initial contrast of the
185 material flux is decreased irreversibly during the ongoing reaction, see **Fig. 3C**, all map sections later
186 than [2]. For comparison, **Fig. 3C** shows the rate evolution during dissolution of KOSSEL crystals with
187 constant defect densities (10, 100, 1000 defects/unit volume). The initial results of the material release
188 s are similar to the above investigations, see **Fig. 3C**, sections 1-2 of both h and l domains and
189 homogeneous crystals with high (1000) and low (10) defect densities. However, the subsequent rate
190 evolution of both layered crystals is similar to those of the homogenous crystal with the lowest defect
191 density (blue dotted line in **Fig. 3C**). Thus, we hypothesize that crystal domains with low defect
192 densities act as inhibitors. Below, we investigate this point in greater detail.

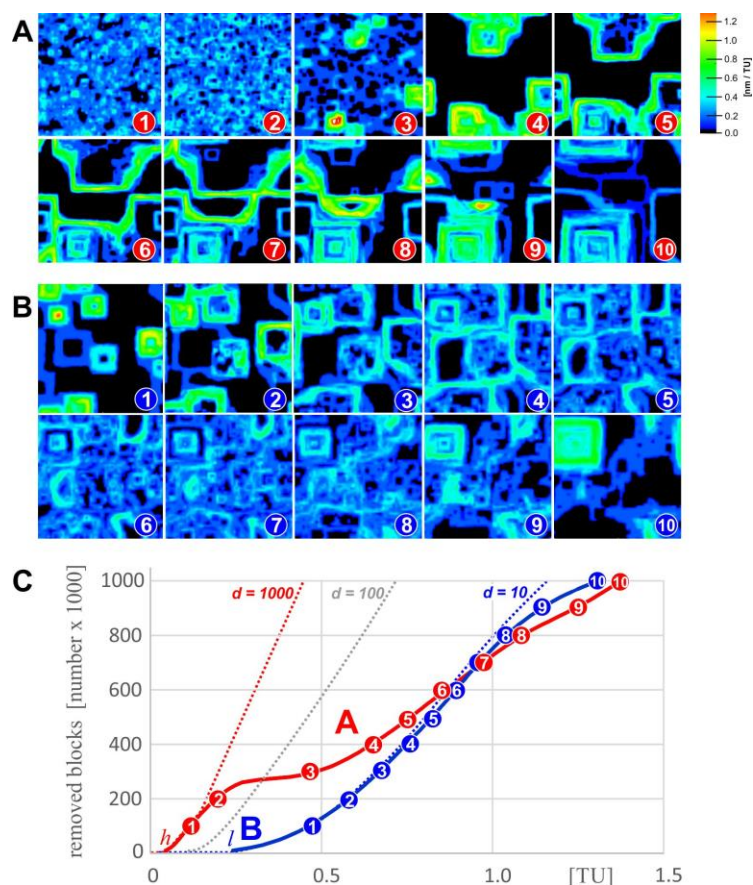


Figure 3: Surface rate evolution of the KOSSEL crystal shown in **Fig. 2**. (A) Rate maps resulting from the dissolution of four layered domains having alternating defect densities, starting with a high defect density (1000 defects/domain), followed by a low defect density (10 defects/domain). (B) Surface rate evolution similar to (A), but starting with a low defect density (10 defects/domain), followed by a high defect density (1000 defects/domain). (C) Evolution of the rate [expressed by total number of removed blocks] of both materials (A) and (B). For comparison, simulation results are shown of single domains having 1000, 100, and 10 defects, respectively. Map size = $300 \times 300 \text{ nm}^2$.

193 3.3 Rate spectra analysis of reaction inhibition

194 We analyzed rate spectra in order to investigate the relationship between reaction kinetics, surface
 195 topography, and potential inhibition of surface reactivity. **Figure 4** illustrates the surface evolution (**Fig.**
 196 **4A-D**) and the respective rate spectra (**Fig. 4A'-D'**). During dissolution of the upper crystal domain,
 197 the evolution of both surface topography and rate spectra reflects the situations of low defect density
 198 (**Fig. 4A, A'**) vs. high defect density (**Fig. 4C, C'**), cf. **Table 1**. Both rate spectra show an asymmetric
 199 shape. The less reactive crystal domain is characterized by a spectrum with a tail towards lower rate
 200 components. Accordingly, the more reactive crystal domain shows the opposite behavior. Then, the
 201 underlying domain gets partly and later completely exposed to dissolution during the ongoing removal
 202 of the upper domain. **Figures 4B, D** illustrate the crystal surface topography after complete removal of

203 the uppermost domain. At this time, both surfaces are dominated by large etch pit structures. It is a
 204 surprising result that the high defect density of the newly exposed material in **Figure 4 B** does not
 205 impact significantly the reaction rate.

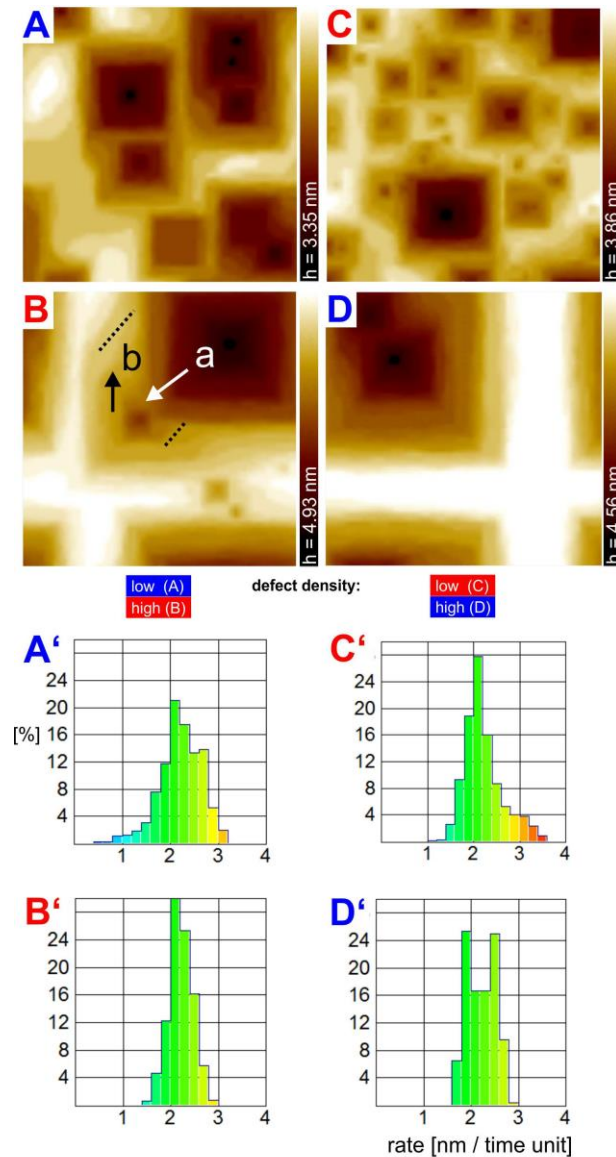


Figure 4: Surface topography and rate spectra evolution of two different layered cake model structures. Left (A,B) with low (blue, upper part) and high (red, lower part) reactivity domains ($dt = 5 \times 10^9$ s). Right (C,D) shows inverse order of domain reactivity ($dt = 6 \times 10^9$ s). Corresponding rate spectra (A', B') and (C', D') are shown below, time unit (TU) = 6×10^9 s. System size = 300×300 nm².

206 Etch pits related to the high defect densities do open and their frequent occurrence is visible at the walls
 207 of the large pit structure. Their spatial evolution is geometrically constrained and hindered by the large
 208 pit structure which produces surface steps much faster than the newly-formed pits. Both the lifetime of
 209 pits and their impact on the overall rate are thus restricted by the final stepwave velocity dictated by the

210 large pit (Lasaga and Luttge, 2001). This result is illustrated by the characteristic shape of the rate
211 spectrum (**Fig. 4B'**). Here, the expected asymmetric shape towards higher rates (cf. **Fig. 4 C'**) is not
212 observed. Instead, the rate spectra shapes of contrasting domains are fairly similar (**Figs. 4 B' and D'**).
213 This result shows that the initial low surface reactivity and the corresponding surface evolution are able
214 to constrain the effective reactivity of a material at later development stages, regardless of its defect
215 density. Thus, a proxy such as defect density is not in general able to serve as an input value for the
216 prediction of reactivity and material flux. Based on defect density we would expect a change to higher
217 material flux and thus a higher reaction rate (**Fig. 4 B, B'**). The rate spectra analysis, however, does
218 show that the expected elevated reactivity of the material is limited due to the previous reaction steps.

219

220 **3.4 Evolution of material flux and surface topography**

221 We investigate the evolution of an important reactive crystal surface site density, i.e., kink sites, and
222 compare their frequency with the evolution of the cumulative material flux (overall void volume) and
223 the rough topography of the reacting surface. In **Figure 5**, the transition between domains of contrasting
224 reactivity is indicated by pairs of dashed lines.

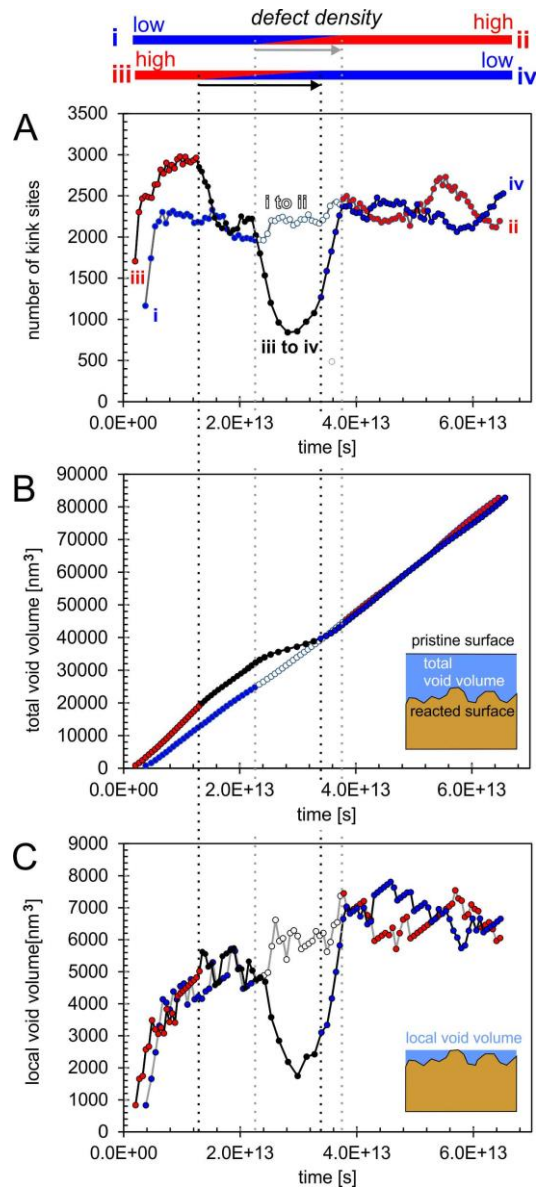


Figure 5: (A) evolution of kink site number, (B) evolution of total dissolved volume, (C) evolution of local void volume (related to rough surface topography) in two different settings (black line, initially high reactivity, gray line: initially low reactivity). Blue and red letters refer to the reactivity of crystal domains, see Fig. 2. Pairs of dashed lines refer to the interface between domains of contrasting reactivity, i.e., initial exposition of underlying domain and complete removal of upper domain.

225 This transition represents the reaction period that starts with the initial exposure of material from the
 226 underlying domain and ends with the complete dissolution of material from the upper domain. The
 227 contrast in reactivity of the upper domains in both systems (low – i vs. high – iii) is illustrated by the
 228 contrast of surface kink site concentration during the initial reaction period (**Fig. 5 A**). Thus, the material
 229 flux from the more reactive domain with higher defect density is higher (red vs. blue circles). While the
 230 void volume formation and the kink site density during this reaction period are not identical, the void
 231 volumes of the rough topographies are similar (**Fig. 5**).

232 This picture changes during the reaction period that is required to remove the material of the
233 upper domain completely. The concentration of kink sites of the highly-reactive domain drops
234 significantly (red \rightarrow black circles; iii \rightarrow iv). This is caused by the high consumption rate of the
235 material of the highly-reactive domain and synchronously the low rate of etch pit and kink site
236 formation in the underlying low-reactivity domain. Consequently, the cumulative material flux
237 decelerates (**Fig. 5 B**) and the corresponding surface pore volume (**Fig. 5 C**) shows a minimum
238 value. One would expect that this picture does reverse after the complete removal of the upper domain
239 of the initially low-reactive crystal (blue \rightarrow open circles; i \rightarrow ii). However, the interesting result is that
240 both the kink site density and the overall material flux of the highly reactive domain (**Figure 5**: open
241 symbols) do not mirror the picture that we observed initially. Instead, the kink site density of both
242 experiments (**Fig. 5 A**, right section) fluctuates around a mean value similar for both systems. Some
243 fluctuations during the dissolution period of the crystal domain with higher defect density (see section
244 (ii)) are caused by an undisturbed growth of newly-formed etch pits. A similar behavior is observed for
245 the void volumes (**Fig. 5 B,C**). These results explain the observations of the limited reaction rates that
246 are illustrated in **Figure 4 B & 4 B'**, see above. Our interpretation is as follows: While the defect density
247 of the highly-reactive domain supports the frequent opening of pits, the life-time of their stepwaves is
248 comparatively short. Consequently, the reactivity of the system is no longer defined by its defect density
249 but rather by the existence of inherited etch pit positions and their large size compared to newly-formed
250 pits (**Fig. 4B**). The position of such pits has been inherited from the previously dissolving domain
251 because the bottom of such deep pits provide the initial exposure to the subjacent crystal domain. As
252 soon as a surface section of the latter had been exposed, the seeding of a new pit started because of the
253 high probability of exposing a defect and opening of a hollow core.

254

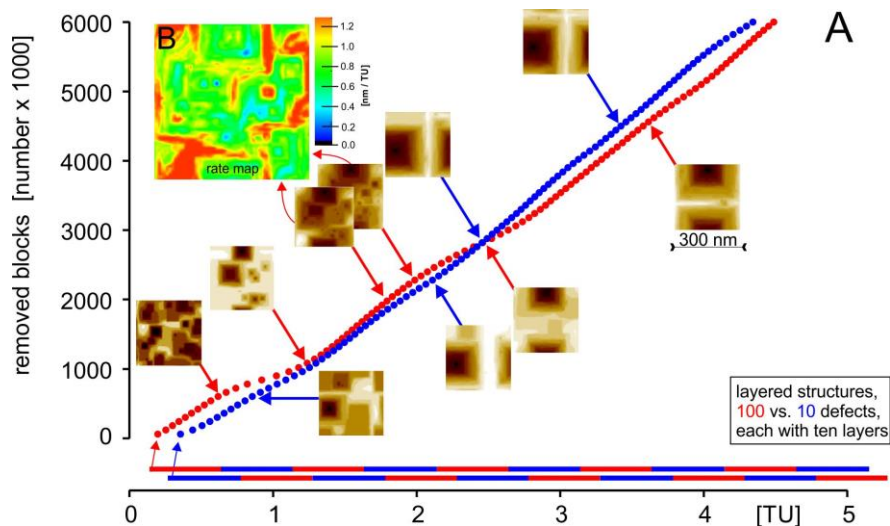


Figure 6: (A) Temporal variability of the material flux of dissolving KOSSEL crystals with 10 domains having alternating reactivity, implemented by the number of defects per domain (10 vs. 1000). The blue-colored curve indicates results of a crystal starting with a low-reactivity domain, the red-colored curve represents a crystals having a high-reactivity starting domain. Topography maps (amber-colored) illustrate the respective topographies. (B) Rate map (topography difference map based on topography maps (38 – 33) identifies large etch pit walls as the source of highest rate portions.

255

256 3.5 Analysis of larger systems

257 The results in **Figs. 3 and 4** suggest the inhibition of surface reactivity by crystal domains with low
 258 reactivity. In this subchapter we ask the question whether this result is valid during the long-term
 259 evolution of dissolution of multiple crystal domains (e.g., Taleb and Stafiej, 2011). We investigate such
 260 behavior by using KOSSEL crystals that consist of a larger number layered domains (**Table 1**). **Figure**
 261 **6** shows the results of the long-term simulations using a system that consists of 10 layers. Here, the
 262 initial sections of the rate curves show the expected contrast, i.e., a higher number of removed blocks
 263 of the highly-reactive surface portion compared to the low reactivity material at the identical time step,
 264 see also **Figure 3C**. Subsequently, both rate curves indicate results that are typical for systems with low
 265 surface reactivity and, thus, low reaction rates. Similar to the shorter simulation runs (**Figs. 2-5**), the
 266 reactivity of the dissolving crystal is dictated by the low-reactivity domains. The surface maps of both
 267 systems explain such behavior (**Fig. 6**). The long-term evolution of the reacting crystal surfaces is
 268 characterized by the evolution of large single pits. This typical result illustrates the dominant growth of
 269 large pits on the expense of small pits. Regardless of the opening of new etch pits, the further growth
 270 of existing large pits is the dominating process (**Fig. 6B**).

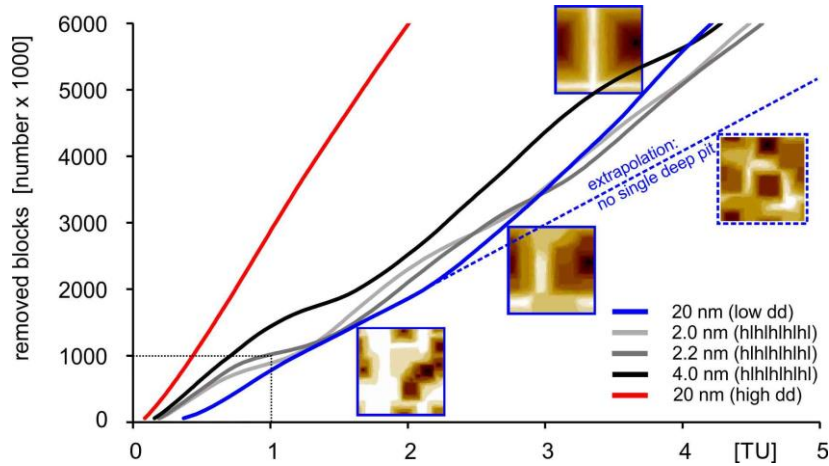


Figure 7: (A) Long-term rate evolution as a function of domain thickness. Three domain thicknesses (2.0, 2.2, 4.0 nm with alternating defect density high vs. low) are investigated. Low (blue) and high (red) defect density (dd) domains are shown for comparison. The dotted line represents a shorter reaction period similar to those analyzed in Figure 3.

271

272 The results in **Figure 7** illustrate the impact of varying domain thickness on the overall reactivity and
 273 material flux during dissolution. The grey-colored lines represent different thicknesses of the alternating
 274 domains (**Table 1**). We compare the results with systems having constant defect densities. Overall, the
 275 reduction in reactivity of the crystals having domains of contrasting defect density is found again,
 276 similar to observations of alloy corrosion (Renner et al., 2006). Our results suggest a complex impact
 277 of the domain thickness on the dissolution of a series of domains. The change of domain thicknesses
 278 causes a non-linear change in reactivity and rates of the compound. Accordingly, both slope and position
 279 of inflection points suggest a complex interplay in-between defect density/ etch pit number, domain
 280 thickness, and material flux/ reaction rate. As an example, the crystal with domain thicknesses = 4.0 nm
 281 shows a higher rate compared to the other examples (2.0 nm and 2.2 nm). Nevertheless, the elevated
 282 reactivity that is represented by the crystal without any domains is not reached during the entire reaction
 283 period. Moreover, the reactivity of this crystal (d = 4.0 nm) having high-reactivity domains drops
 284 temporarily below the reactivity of the low-defect density crystal. Geometrical constraints related to the
 285 evolution of rough surface topography during the etch pit growth are a potential explanation.

286 **Figure 7** illustrates another important characteristics of any reacting crystal, exemplified by the blue-
 287 colored rate curve. During the comparatively long reaction period, the reaction rate increases as shown
 288 by the deviation from the dashed line. Such behavior can be explained by the occurrence of large etch

289 pit walls having high kink site densities as the major portion of the overall crystal surface. Similar
290 results have been reported for the dissolution reaction of grains of single crystals (Briese et al., 2017;
291 Petrik and Harbrecht, 2013). Thus, an additional important parameter that exerts control on the system's
292 reactivity is the domain size and the related opportunity to form large etch pits with a characteristic high
293 surface roughness and topography.

294 Previous attempts to quantify the surface rates vs. etch pit nucleation focused on pit size distribution
295 analysis (MacInnis and Brantley, 1993). Such approaches compared the varying size, distribution, and
296 coalescence of pits with reaction rates of single crystal surfaces (Luttge, 2005). Experimental
297 approaches showed how spatial heterogeneities in both surface kinetics and material transport properties
298 evolve during single crystal dissolution (Peruffo et al., 2013). As a result, the morphology of the
299 characteristic etch features may reveal direction-dependent dissolution kinetics. Our approach utilizes
300 this knowledge and applies it to more complex model systems in order to extract important new
301 information about the evolution of reactivity. More specifically, the temporal evolution of rate spectra
302 informs about material flux variability and relates it to etch pit formation, growth, and coalescence
303 (Fischer and Luttge, 2017). Rate acceleration and rate jerk data suggested the pulsating behavior of
304 surface reactivity (Fischer and Luttge, 2018). Overall, the modeling results focusing on varying defect
305 density underscore the critical role of reactivity anisotropy in crystalline material for the evolution of
306 surface roughness and void volume pattern due to dissolution. More specifically, these results show
307 how the spatial distribution of high vs. low reactivity domains in crystal grains impacts the evolution
308 of void volume patterns in materials that are characterized by an identical mean defect density. This
309 approach might thus serve as an example of how the present KMC results are applicable to explain the
310 formation of initial pattern of void volume in solids. Examples include the corrosion of steel (Sun et al.,
311 2015), the formation of secondary porosity due to contrasting defect density pattern in feldspar grains
312 and cements (González-Acebrón et al., 2012; Götze et al., 2000), and the dissolution in battery
313 electrolyte (Steiger et al., 2014). For such systems, we expect the existence of concurrent mechanisms
314 that affect surface reactivity. Such mechanisms include passivation processes during mineral surface
315 reactions due to the formation of altered surface layers (e.g., Daval et al., 2011; Wild et al., 2016).

316

317 **5 Conclusions**

318 The analysis of Kinetic Monte Carlo simulation results by employing the rate spectra concept provides
319 new insight into the reactivity of crystalline material. The combination of new results about the
320 reduction in reactivity of highly-reactive crystal domains with the quantitative concept of rate spectra
321 may serve as a base for the development of a powerful tool to predict the reactivity of complex
322 crystalline materials. In detail we conclude: The reactivity of a crystalline system can be governed by
323 its reaction history. The dissolution of low-reactivity domains within crystalline matter defines the
324 subsequent reactivity. Crystal domains with high defect densities inherit a lower reactivity close to
325 reacting crystal domains with lower defect densities. Such a mechanism contributes to the explanation
326 of the reduction in surface reactivity of polycrystalline materials. Our results provide a quantitative
327 background to answer questions related to corrosion and dissolution in the material and earth sciences,
328 such as the predetermination of void volume formation with consequences for permeability evolution,
329 as well as for radioactive waste management problems that involve materials with contrasting defect
330 densities.

331

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338 **References**

- 339 Anbeek, C., 1992. Surface-Roughness of Minerals and Implications for Dissolution Studies.
340 *Geochimica et Cosmochimica Acta* 56, 1461-1469.
- 341 Anbeek, C., Vanbreemen, N., Meijer, E.L., Vanderplas, L., 1994. The Dissolution of
342 Naturally Weathered Feldspar and Quartz. *Geochimica et Cosmochimica Acta* 58, 4601-
343 4613.
- 344 Anovitz, L.M., Cole, D.R., 2015. Characterization and analysis of porosity and pore
345 structures. *Reviews in Mineralogy and Geochemistry* 80, 61-164.
- 346 Blum, A.E., Lasaga, A.C., 1987. Monte Carlo simulations of surface reaction rate laws., in:
347 Stumm, W. (Ed.), *Aquatic Surface Chemistry: Chemical Processes at the ParticleWater*
348 *Interface*. John Wiley and Sons, Inc., pp. 255–292.

349 Bortz, A.B., Kalos, M.H., Lebowitz, J.L., 1975. A new algorithm for Monte Carlo simulation
350 of Ising spin systems. *Journal of Computational Physics* 17, 10-18.

351 Briese, L., Arvidson, R.S., Luttge, A., 2017. The effect of crystal size variation on the rate of
352 dissolution – A kinetic Monte Carlo study. *Geochimica et Cosmochimica Acta* 212, 167-175.

353 Burton, W.K., Cabrera, N., Frank, F.C., 1951. The Growth of Crystals and the Equilibrium
354 Structure of Their Surfaces. *Philosophical Transactions of the Royal Society of London*
355 *Series a-Mathematical and Physical Sciences* 243, 299-358.

356 Cama, J., Zhang, L., Soler, J.M., De Giudici, G., Arvidson, R.S., Luttge, A., 2010. Fluorite
357 dissolution at acidic pH: In situ AFM and ex situ VSI experiments and Monte Carlo
358 simulations. *Geochimica et Cosmochimica Acta* 74, 4298-4311.

359 Casey, W.H., Carr, M.J., Graham, R.A., 1988. Crystal Defects and the Dissolution Kinetics
360 of Rutile. *Geochimica et Cosmochimica Acta* 52, 1545-1556.

361 Chen, L., Kang, Q., Carey, B., Tao, W.-Q., 2014. Pore-scale study of diffusion–reaction
362 processes involving dissolution and precipitation using the lattice Boltzmann method.
363 *International Journal of Heat and Mass Transfer* 75, 483-496.

364 Cheng, V.K.W., 1993. A Monte Carlo study of moving steps during crystal growth and
365 dissolution. *Journal of Crystal Growth* 134, 369-376.

366 Daval, D., Hellmann, R., Saldi, G.D., Wirth, R., Knauss, K.G., 2013. Linking nm-scale
367 Measurements of the Anisotropy of Silicate Surface Reactivity to Macroscopic Dissolution
368 Rate Laws: New Insights Based on Diopside. *Geochimica et Cosmochimica Acta* 107, 121-
369 134.

370 Daval, D., Sissmann, O., Menguy, N., Saldi, G.D., Guyot, F., Martinez, I., Corvisier, J.,
371 Garcia, B., Machouk, I., Knauss, K.G., R., H., 2011. Influence of amorphous silica layer
372 formation on the dissolution rate of olivine at 90 °C and elevated pCO₂. *Chemical Geology*
373 284, 193-209.

374 Dele-Afolabi, T.T., Hanim, M.A.A., Norkhairunnisa, M., Sobri, S., Calin, R., Investigating
375 the effect of porosity level and pore former type on the mechanical and corrosion resistance
376 properties of agro-waste shaped porous alumina ceramics. *Ceramics International*.

377 Dillinger, A., Ricard, L.P., Huddleston-Holmes, C., Esteban, L., 2014. Impact of Diagenesis
378 on Reservoir Quality in a Sedimentary Geothermal Play: a case study in the Cooper Basin,
379 South Australia. *Basin Research*, 1-21.

380 Dong, Y., Lin, B., Zhou, J.-e., Zhang, X., Ling, Y., Liu, X., Meng, G., Hampshire, S., 2011.
381 Corrosion resistance characterization of porous alumina membrane supports. *Materials*
382 *Characterization* 62, 409-418.

383 Dove, P.M., Han, N.Z., De Yoreo, J.J., 2005. Mechanisms of classical crystal growth theory
384 explain quartz and silicate dissolution behavior. *Proceedings of the National Academy of*
385 *Sciences of the United States of America* 102, 15357-15362.

386 Fischer, C., Arvidson, R.S., Luttge, A., 2012. How predictable are dissolution rates of
387 crystalline material? *Geochimica et Cosmochimica Acta* 98, 177-185.

388 Fischer, C., Kurganskaya, I., Schäfer, T., Luttge, A., 2014. Variability of Crystal Surface
389 Reactivity: What do we know? (Review Article). *Applied Geochemistry* 43, 132-157.

390 Fischer, C., Luttge, A., 2017. Beyond the conventional understanding of water–rock
391 reactivity. *Earth and Planetary Science Letters* 457, 100-105.

392 Fischer, C., Luttge, A., 2018. Pulsating dissolution of crystalline matter. *PNAS* in press.

393 Gao, J., Xing, H., Tian, Z., Pearce, J.K., Sedek, M., Golding, S.D., Rudolph, V., 2017.
394 Reactive transport in porous media for CO₂ sequestration: Pore scale modeling using the
395 lattice Boltzmann method. *Computers & Geosciences* 98, 9-20.

396 González-Acebrón, L., Götze, J., Barca, D., Arribas, J., Mas, R., Pérez-Garrido, C., 2012.
397 Diagenetic albitization in the Tera Group, Cameros Basin (NE Spain) recorded by trace
398 elements and spectral cathodoluminescence. *Chemical Geology* 312–313, 148-162.

399 Götze, J., Krbetschek, M., Habermann, D., Wolf, D., 2000. High-Resolution
400 Cathodoluminescence Studies of Feldspar Minerals, in: Pagel, M., Barbin, V., Blanc, P.,
401 Ohnenstetter, D. (Eds.), Cathodoluminescence in Geosciences. Springer Berlin Heidelberg,
402 pp. 245-270.

403 Hellevang, H., Pham, V.T.H., Aagaard, P., 2013. Kinetic modelling of CO₂-water-rock
404 interactions. *International Journal of Greenhouse Gas Control* 15, 3-15.

405 Hiemstra, T., van Riemsdijk, W.H., 1999. Effect of different crystal faces on experimental
406 interaction force and aggregation of hematite. *Langmuir* 15, 8045-8051.

407 Horlait, D., Claparede, L., Tocino, F., Clavier, N., Ravaux, J., Szenknect, S., Podor, R.,
408 Dacheux, N., 2014. Environmental SEM Monitoring of Ce_{1-x}Ln_xO_{2-x/2} mixed-oxide
409 Microstructural Evolution during Dissolution. *Journal of Materials Chemistry A* 2, 5193-
410 5203.

411 Iliiev, O., Lakdawala, Z., Leonard, K., Vutov, Y., 2015. On pore--scale modeling and
412 simulation of reactive transport in 3D geometries. arXiv preprint arXiv:1507.01894.

413 Kerisit, S., Rosso, K.M., Cannon, B.D., 2008. Kinetic Monte Carlo model of scintillation
414 mechanisms in CsI and CsI(Tl). *Ieee Transactions on Nuclear Science* 55, 1251-1258.

415 Kim, J.-S., Kwon, S.-K., Sanchez, M., Cho, G.-C., 2011. Geological storage of high level
416 nuclear waste. *KSCE Journal of Civil Engineering* 15, 721-737.

417 Kossel, W., 1927. Zur Theorie des Kristallwachstums. *Nachrichten von der Gesellschaft der*
418 *Wissenschaften zu Göttingen, Mathematisch-Physikalische Klasse* 1927, 135-143.

419 Kurganskaya, I., Luttge, A., 2016. Kinetic Monte Carlo Approach To Study Carbonate
420 Dissolution. *The Journal of Physical Chemistry C* 120, 6482-6492.

421 Lasaga, A.C., Blum, A.E., 1986. Surface chemistry, etch pits and mineral-water reactions.
422 *Geochimica et Cosmochimica Acta* 50, 2363-2379.

423 Lasaga, A.C., Luttge, A., 2001. Variation of Crystal Dissolution Rate Based on a Dissolution
424 Stepwave Model. *Science* 291, 2400-2404.

425 Lasaga, A.C., Luttge, A., 2004. Mineralogical approaches to fundamental crystal dissolution
426 kinetics. *American Mineralogist* 89, 527-540.

427 Liu, Y., Lopes, P.P., Cha, W., Harder, R., Maser, J., Maxey, E., Highland, M.J., Markovic,
428 N.M., Hruszkewycz, S.O., Stephenson, G.B., You, H., Ulvestad, A., 2017. Stability Limits
429 and Defect Dynamics in Ag Nanoparticles Probed by Bragg Coherent Diffractive Imaging.
430 *Nano Letters* 17, 1595-1601.

431 Liu, Y., Luo, Y., Elzatahry, A.A., Luo, W., Che, R., Fan, J., Lan, K., Al-Enizi, A.M., Sun, Z.,
432 Li, B., Liu, Z., Shen, D., Ling, Y., Wang, C., Wang, J., Gao, W., Yao, C., Yuan, K., Peng, H.,
433 Tang, Y., Deng, Y., Zheng, G., Zhou, G., Zhao, D., 2015. Mesoporous TiO₂ Mesocrystals:
434 Remarkable Defects-Induced Crystallite-Interface Reactivity and Their in Situ Conversion to
435 Single Crystals. *ACS Central Science* 1, 400-408.

436 Luttge, A., 2005. Etch pit coalescence, surface area, and overall mineral dissolution rates.
437 *American Mineralogist* 90, 1776-1783.

438 Luttge, A., Arvidson, R.S., Fischer, C., 2013. A Stochastic Treatment of Crystal Dissolution
439 Kinetics. *Elements* 9, 183-188.

440 MacInnis, I.N., Brantley, S.L., 1993. Development of Etch Pit Size Distributions on
441 Dissolving Minerals. *Chemical Geology* 105, 31-49.

442 Meakin, P., Rosso, K.M., 2008. Simple kinetic Monte Carlo models for dissolution pitting
443 induced by crystal defects. *Journal of Chemical Physics* 129.

444 Michaelis, M., Fischer, C., Colombi Ciacchi, L., Luttge, A., 2017. Variability of Zinc Oxide
445 Dissolution Rates. *Environmental Science & Technology* 51, 4297-4305.

446 Monger, H.C., Kraimer, R.A., Khresat, S., Cole, D.R., Wang, X., Wang, J., 2015.
447 Sequestration of inorganic carbon in soil and groundwater. *Geology* 43, 375-378.

448 Mostaghimi, P., Liu, M., Arns, C.H., 2016. Numerical Simulation of Reactive Transport on
449 Micro-CT Images. *Mathematical Geosciences*, 1-21.

450 Pelmenschikov, A., Leszczynski, J., Pettersson, L.G.M., 2001. Mechanism of Dissolution of
451 Neutral Silica Surfaces: Including Effect of Self-Healing. *The Journal of Physical Chemistry*
452 *A* 105, 9528-9532.

453 Peruffo, M., Mbogoro, M.M., Edwards, M.A., Unwin, P.R., 2013. Holistic approach to
454 dissolution kinetics: linking direction-specific microscopic fluxes, local mass transport effects
455 and global macroscopic rates from gypsum etch pit analysis. *Physical Chemistry Chemical*
456 *Physics* 15, 1956-1965.

457 Petrik, M., Harbrecht, B., 2013. Dissolution Kinetics of Nanocrystals. *ChemPhysChem* 14,
458 2403-2406.

459 Renner, F.U., Stierle, A., Dosch, H., Kolb, D.M., Lee, T.L., Zegenhagen, J., 2006. Initial
460 corrosion observed on the atomic scale. *Nature* 439, 707-710.

461 Saldi, G.D., Voltolini, M., Knauss, K.G., 2017. Effects of surface orientation, fluid chemistry
462 and mechanical polishing on the variability of dolomite dissolution rates. *Geochimica et*
463 *Cosmochimica Acta* 206, 94-111.

464 Steefel, C.I., Beckingham, L.E., Landrot, G., 2015. Micro-continuum approaches for
465 modeling pore-scale geochemical processes. *Reviews in Mineralogy and Geochemistry* 80,
466 217-246.

467 Steiger, J., Kramer, D., Mönig, R., 2014. Microscopic observations of the formation, growth
468 and shrinkage of lithium moss during electrodeposition and dissolution. *Electrochimica Acta*
469 136, 529-536.

470 Stranski, I.N., 1928. On the theory of crystal accretion. *Zeitschrift Fur Physikalische Chemie-*
471 *Stoichiometrie Und Verwandtschaftslehre* 136, 259-278.

472 Sun, G., Zhou, R., Lu, J., Mazumder, J., 2015. Evaluation of defect density, microstructure,
473 residual stress, elastic modulus, hardness and strength of laser-deposited AISI 4340 steel.
474 *Acta Materialia* 84, 172-189.

475 Taleb, A., Stafiej, J., 2011. Numerical simulation of the effect of grain size on corrosion
476 processes: Surface roughness oscillation and cluster detachment. *Corrosion Science* 53, 2508-
477 2513.

478 Tang, R.K., Henneman, Z.J., Nancollas, G.H., 2003. Constant composition kinetics study of
479 carbonated apatite dissolution. *Journal of Crystal Growth* 249, 614-624.

480 Taylor, T.R., Giles, M.R., Hathon, L.A., Diggs, T.N., Braunsdorf, N.R., Birbiglia, G.V.,
481 Kittridge, M.G., Macaulay, C.I., Espejo, I.S., 2010. Sandstone diagenesis and reservoir
482 quality prediction: Models, myths, and reality. *AAPG Bulletin* 94, 1093-1132.

483 Thomas, T.R., 1999. *Rough Surfaces*. Imperial College Press, London.

484 Walrafen, G.E., 1972. Raman and Infrared Spectral Investigations of Water Structure, in:
485 Franks, F. (Ed.), *Water, A Comprehensive Treatise*, Vol. 1. The Physics and Physical
486 Chemistry of Water. Plenum, New York.

487 Wild, B., Daval, D., Guyot, F., Knauss, K.G., Pollet-Villard, M., Imfeld, G., 2016. pH-
488 dependent control of feldspar dissolution rate by altered surface layers. *Chemical Geology*
489 442, 148-159.

490 Xu, G., Chen, Z., Zhang, X., Cui, H., Zhang, Z., Zhan, X., 2016. Preparation of porous
491 Al₂TiO₅-Mullite ceramic by starch consolidation casting and its corrosion resistance
492 characterization. *Ceramics International* 42, 14107-14112.

493 Yang, F., Hingerl, F.F., Xiao, X., Liu, Y., Wu, Z., Benson, S.M., Toney, M.F., 2015.
494 Extraction of pore-morphology and capillary pressure curves of porous media from
495 synchrotron-based tomography data. *Sci. Rep.* 5.

496

497