INTRODUCTION

Minerals precipitated in veins, shear zones and extensional fractures can be used to track diverse processes including brittle and ductile deformation (van der Pluijm et al., 2001), ore genesis (Oze et al., 2017), fluid migration and mixing (Uysal et al., 2011) and ancient microbial activity (Drake et al., 2015). Once a discontinuity in the bedrock has formed, repeated reactivation may result in a record of multiple authigenic mineral generations precipitated along fault planes (e.g., slickenfibres) and walls of re-opened fractures, forming poly-phased veins (Bons et al., 2012; Sibson et al., 1975). Direct dating of (a) calcite infill in veins (e.g., Nuriel et al., 2012; Roberts et al., 2020), (b) illite in fault gouge (e.g., Uysal et al., 2020; Viola et al., 2016), (c) illite-K-feldspar-calcite slickenfibres (Tillberg et al., 2020) and (d) sulphides in faults and veins (Saintilan et al., 2017; Vernon et al., 2014) has indicated that episodic reactivation and fluid flow can be constrained by absolute time stamps.

Dating of fault gouge and veins has shown that faults record reactivation and mineral neo-crystallization in various tectonic regimes, including rifting (Scheiber et al., 2019) and shearing of conjugate faults (Goodfellow et al., 2017). Crust within Precambrian cratons usually experienced complex histories of tectonically induced episodic fracture reactivation. These tectonic effects can act in the far-field over entire cratons and include compression, shearing or extension of crustal blocks, for example, due to foreland basin development and crustal thickening, or mountain range build-up and collapse (e.g., Andersen, 1998). Vein mineralization dating is well suited to decipher the complex tectonic evolution of cratons. However, no attempts have yet been made to (a) use micro-scale geochronology to decipher multi-stage reactivation of ductile shear fractures with regional-scale crustal dynamic responses to tectonic events.
zones and of sub-mm-sized veinlets of discrete fracture networks within Precambrian cratons and (b) interpolate such age populations between sites in a craton for detailed reconstructions of tectonic-related effects on crustal blocks. Here, we apply in situ Rb-Sr geochronology on impact breccia (Jourdan & Reimold, 2012). Previously dated fracture fillings that yielded a 40Ar/39Ar age at 989 ± 3 Ma of adularia at Forsmark (Sandström et al., 2009) and in situ Rb-Sr and Sr-rich (calcite, albite, laumontite, epidote, harmotome and fluorite) minerals identified by SEM-EDS was conducted by laser ablation triple quadrupole inductively coupled plasma mass spectrometry (LA-ICP-MS/MS). Multi-collector LA-ICP-MS analysis of calcite was performed to obtain initial 87Sr/86Sr values. Control of closed system conditions and synchronous isotopic fixation in the minerals included in valid Rb-Sr isochron dating is based on the microtextural petrographic analysis and the isotopic compositions from laser ablation signals recognizing any heterogeneities, inclusions and other impurities in veins, grains and crystal zonation. Detailed information regarding analytical set-up and data reduction is provided in Supplementary Note. All sample and standard data are listed in Datasets S1–S3, along with fracture orientations (for Laxemar and Forsmark).

2 | DATING METHOD

Veins and fracture coatings from depths from 15–642 m (n = 7 at Laxemar, n = 7 at Forsmark, n = 5 at Siljan) were characterized texturally by petrographic microscope, and scanning electron microscope coupled to an energy dispersive spectrometer (SEM-EDS). Rb-Sr geochronology of discrete zones in co-genetic Rb-rich (illite, K-feldspar) and Sr-rich (calcite, albite, laumontite, epidote, harmotome and fluorite) minerals identified by SEM-EDS was conducted by laser ablation triple quadrupole inductively coupled plasma mass spectrometry (LA-ICP-MS/MS). Multi-collector LA-ICP-MS analysis of calcite was performed to obtain initial 87Sr/86Sr values. Control of closed system conditions and synchronous isotopic fixation in the minerals included in valid Rb-Sr isochron dating is based on the microtextural petrographic analysis and the isotopic compositions from laser ablation signals recognizing any heterogeneities, inclusions and other impurities in veins, grains and crystal zonation. Detailed information regarding analytical set-up and data reduction is provided in Supplementary Note. All sample and standard data are listed in Datasets S1–S3, along with fracture orientations (for Laxemar and Forsmark).

3 | RESULTS AND DISCUSSION

A total of 27 Rb-Sr isochrons from 19 samples (Table 1) were derived for a variety of mineralization assemblages and structures (Dataset S1) and group into several age populations. Petrographic and geochronological characteristics of the episodic mineralization on individual vein- and/or grain-scale, and their relation to tectonic episodes affecting the Fennoscandian Shield on the craton-scale, are presented below.
TABLE 1 Sample, age, age error (2σ absolute), minerals, mean square weighted deviation (MSWD) and initial $^{87}\text{Sr}/^{86}\text{Sr}$ values of each respective isochron produced in this study

| Sample       | Age (Ma)         | Minerals (n = spots) | MSWD | Initial $^{87}\text{Sr}/^{86}\text{Sr}$ |
|--------------|------------------|----------------------|------|------------------------------------------|
| Forsmark     |                  |                      |      |                                          |
| KFM01B:433m  | 1.447 ± 45       | kf (n = 5), lau (n = 3), ab (n = 1) | 1.70 | 0.7060 ± 0.0038                          |
| KFM01C:73m   | 387 ± 10         | kf (n = 5), cc (n = 1) | 1.50 | 0.71446 ± 0.00016                        |
| KFM02B:171m  | 1.476 ± 20       | kf (n = 10), cc (n = 1) | 0.40 | 0.70732 ± 0.00020                        |
| KFM04A:306m  | 355 ± 12         | kf (n = 8), cc (n = 2) | 0.41 | 0.715119 ± 0.000039                      |
| KFM04A:306m  | 1.429 ± 18       | kf (n = 4), cc (n = 1) | 1.40 | 0.7110 ± 0.0027                          |
| KFM06C:391m  | 402 ± 23         | kf (n = 3), cc (n = 1) | 0.02 | 0.71636 ± 0.00016                        |
| KFM06C:391m  | 1.476 ± 14       | kf (n = 15), cc (n = 1) | 1.60 | 0.70909 ± 0.00016                        |
| KFM15:15m    | 1.123 ± 16       | ill (n = 3), kf (n = 4), ab (n = 2), cc (n = 2) | 0.67 | 0.7117 ± 0.0052                          |
| KFM24:399m   | 1.495 ± 55       | kf (n = 4), cc (n = 1) | 0.098 | 0.7089 ± 0.0061                         |
| Laxemar      |                  |                      |      |                                          |
| KA1755:151m  | 1.430 ± 12       | ms (n = 7), cc (n = 1) | 1.04 | 0.7080 ± 0.0018                         |
| KA1755:151m  | 1.757 ± 15       | ms (n = 3), ab (n = 2) | 0.61 | 0.7062 ± 0.0022                         |
| KLOX0:1220m  | 677 ± 11         | kf (n = 6), cc (n = 1) | 0.60 | 0.711258 ± 0.000051                      |
| KLOX0:2220m  | 1.436 ± 18       | kf (n = 11), cc (n = 1) | 0.31 | 0.706852 ± 0.000045                      |
| KLOX0A:357m  | 681 ± 21         | kf (n = 4), cc (n = 1) | 0.18 | 0.7133 ± 0.0018                          |
| KSH01A:600m  | 392 ± 13         | kf (n = 4), cc (n = 1) | 0.89 | 0.7122 ± 0.0035                         |
| KSH03A:186m  | 3577 ± 7.7       | ill (n = 9), cc (n = 1) | 0.24 | 0.712188 ± 0.00003                      |
| KSH03A:186m  | 393.8 ± 7.8      | ill (n = 11), ep (n = 1) | 0.69 | 0.7100 ± 0.0078                         |
| KSH03A:197m  | 449 ± 12         | kf (n = 3), cc (n = 3) | 1.11 | 0.7094 ± 0.0018                         |
| KSH03A:225m  | 444 ± 12         | kf (n = 4), cc (n = 2) | 0.96 | 0.7111 ± 0.0049                         |
| Siljan       |                  |                      |      |                                          |
| CC1:539m     | 1.447 ± 50       | kf (n = 6), cc (n = 1) | 0.44 | 0.7089 ± 0.0037                         |
| CC1:539m     | 1.680 ± 43       | kf (n = 3), cc (n = 3) | 1.50 | 0.7043 ± 0.0035                         |
| Solb1:395m   | 1.299 ± 36       | kf (n = 5), fl (n = 1) | 1.30 | 0.7080 ± 0.0130                         |
| Solb1:395m   | 1.488 ± 31       | kf (n = 4), ab (n = 1) | 1.00 | 0.7073 ± 0.0051                         |
| Solb1:436m   | 1.433 ± 30       | kf (n = 5), ha (n = 2) | 0.99 | 0.7083 ± 0.0069                         |
| Solb1:436m   | 1.670 ± 100      | kf (n = 5), ab (n = 3) | 0.19 | 0.7050 ± 0.0140                         |
| VM2:333m     | 447 ± 37         | ill (n = 12), cc (n = 1) | 0.20 | 0.71623 ± 0.00041                       |
| VM2:642m     | 445 ± 12         | ill (n = 4), kf (n = 3), cc (n = 1) | 0.72 | 0.72221 ± 0.00014                       |

Abbreviations: ab, albite; cc, calcite; ep, epidote; fl, fluorite; ha, harmotome; ill, illite; kf, K-feldspar; lau, laumontite; ms, muscovite.

3.1 | Mineral precipitation age clusters

The oldest age determined in the study is from K-feldspar-albite fabric in a Laxemar mylonite (1757 ± 15 Ma). The oldest ages at Siljan (1,680 ± 43 and 1,670 ± 100 Ma) are from K-feldspar + calcite ± albite (nuclei in zoned vein crystals).

Mesoproterozoic ages between 1,495 ± 55-1,429 ± 18 Ma are most frequently observed (n = 10), and occur in all areas. These ages are mainly from K-feldspar-calcite assemblages in veins, such as in Forsmark (Figure 2), but also from K-feldspar + calcite ± albite ± harmotome assemblages at Siljan, overgrowing the 1.68-1.67 Ga group. At Laxemar, Mesoproterozoic neo-crystallization of K-feldspar is documented in the 1757 ± 15 Ma mylonite zone (Figure 3f-i).

Although partially overlapping each other, there are two possible sub-clusters at 1,495 ± 55-1,476 ± 20 Ma (n = 5) and at 1,447 ± 50-1,429 ± 18 Ma (n = 5).

At Siljan, 1,299 ± 36 Ma K-feldspar-fluorite overgrew 1,488 ± 31 Ma K-feldspar-albite, whereas a slightly younger K-feldspar-illite-calcite-albite age at 1,123 ± 16 Ma were determined at Forsmark.

Two closely spaced K-feldspar-calcite ages, 681 ± 21 and 677 ± 11 Ma, occur at Laxemar, in one case overgrowing a 1,436 ± 18 Ma assemblage (Figure 3a). Palaeozoic ages (n = 10) occur in three clusters, starting with K-feldspar ± calcite ± illite vein assemblages (449 ± 12-444 ± 12 Ma, n = 4) at Siljan and Laxemar (Figure 3c-e-j-l); 402 ± 23-387 ± 10 Ma (n = 4) K-feldspar-calcite veins follow, overgrowing Mesoproterozoic minerals and
illite-calcite veins at Laxemar and Forsmark. At these sites, there are also two younger ages: 358 ± 8 Ma illite-calcite neo-crystallization (Figure 3b) and 355 ± 12 Ma overgrowths on Mesoproterozoic K-feldspar-calcite precursors.

3.2 | Linkage of fracture activation/reactivation to tectonic events

$^{40}$Ar/$^{39}$Ar closure ages of TIB hornblende indicate rapid cooling down to ~500°C shortly after the 1.8 Ga TIB rock emplacement at Laxemar (Söderlund et al. 2008). This is in agreement with our 1757 ± 15 Ma-aged K-feldspar-albite fabric in a major semi-ductile NE-trending shear zone (Figure 3f-i). At Siljan, the oldest ages are close to the formation ages of the youngest granite emplacement in the area (Ahl et al., 1999), and we therefore interpret the oldest mineral assemblages in the Siljan fractures to reflect fluid circulation related to local magmatism.

Brander (2011) described extension across central Sweden at the Danopolonian-Hallandian tectonic event (1.47-1.44 Ga), which is recognized across the southern Scandinavia (Söderlund et al., 2008). This is in temporal correspondence with several of the vein mineral assemblages (Figure 4), including reactivation of a ductile shear zone at Laxemar. We therefore propose that this tectonic event caused fracture formation in the crystalline bedrock and reactivation of shear zones throughout the craton. At Forsmark, these fractures are steeply dipping and NNE-striking (Figures 2 and 3, Dataset S1), which suggest ESE-WNW-directed extension. The mineralization ages between 1.49-1.47 Ga at Forsmark and Siljan mark an early phase of the Danopolonian-Hallandian extensional event, and/or...
extension related to Rapakivi granite magmatism in eastern parts of the craton (Söderlund et al., 2008). At Laxemar, there are also veins directly related to hydrothermal fluid circulation and greisenization introduced by local granite intrusions of Danopolonian-Hallandian association (Tillberg et al., 2019). The 1,299 ± 36 Ma K-feldspar-fluorite mineralization at Siljan temporally overlaps, and may thus be related to 1.27–1.26 Ga mafic magmatism and related crustal extension near Siljan (Söderlund et al., 2006).

At Forsmark, fracture reactivation occurred in a transpressional tectonic regime in the E-W direction during the Sveconorwegian Orogeny (Saintot et al., 2011). Rb-Sr dating of slickenfibre K-feldspar-calcite (1,074 ± 74 Ma, Tillberg et al., 2020) has temporally confirmed Sveconorwegian fault reactivations of the fracture sets described in Saintot et al. (2011). This event is further time-constrained by our 1,123 ± 16 Ma age and the 1107–1034 Ma adularia ages of Sandström et al. (2009).

The structural evolution of the period between the Sveconorwegian and Caledonian Orogens is scarcely described in the literature. Along with ~697 Ma fault minerals in southern Finland (Elminen et al., 2018), our vein mineral ages at 681 ± 21 and 677 ± 11 Ma (Figure 3a) provide the first indication of fracture reactivation in the Fennoscandian Shield at these times, probably influenced by up to 6–7-km-thick foreland basin development (Guenthner et al., 2017).

The Caledonian Orogeny affected NW parts of Fennoscandian Shield in the Late Cambrian to Early Devonian (Roberts, 2003), with a main “Scandian” stage of collision and subsequent orogenic collapse between 430 and 380 Ma (Corfu et al., 2014). Hence, we relate the 447 ± 37–444 ± 12 Ma old adularia-calcite ± illite vein assemblages at Laxemar and Siljan (Figures 3 and 4) to far-field effects related to a pre-Scandian tectonic event in the Caledonides. Our studied fracture sets show no straightforward orientation trend (Figure 3), but previous investigations found a dominance of WNW–ESE-directed fractures carrying the same mineral assemblage (Drake et al., 2009), in agreement with direction of the Caledonian bulk crustal shortening (Roberts, 2003).

During post-orogenic collapse of the Caledonides after ca. 408 Ma (Andersen, 1998), a foreland basin had started to develop on the Fennoscandian shield to the ESE-SSE of the orogenic belt (Cederbom, 2001). This development probably featured local extensional stress directed perpendicular to the orogen, in response to a migrating forebulge (Alm et al., 2005). The most frequently detected Palaeozoic vein mineral ages cluster between 402 ± 23–387 ± 10 Ma at Laxemar and Forsmark (Figures 3 and 4). These mainly occur in steep NNE-striking fractures, including fractures with Mesoproterozoic mineral precursors (Figure 2, Dataset S1). Consequently, we correlate this event of fracture activation/reactivation to WNW–ESE-directed extension following orogenic collapse and foreland basin initiation.

Thermochronological constraints exist for heating of the wall rock minerals at Laxemar to 150°C during the peak thickness of the Caledonian foreland basin (Guenthner et al., 2017). We propose that the 358 ± 8–355 ± 12 Ma adularia ± illite ± calcite formation in reactivated veins at Laxemar and Forsmark occurred during foreland basin development featuring enhanced fluid circulation induced by the increased heat and tectonics associated with crustal
FIGURE 3 Linkage of isochrons, mineralogy, petrographic textures, structural orientations and borehole locations for Laxemar and Forsmark samples. (a) Isochrons and back-scattered electron (BSE) images showing grain zonations in sample KLX01:220m. Isochron $1,436 \pm 18$ Ma: Mean square weighted deviation (MSWD) = 0.31, initial $^{87}$Sr/$^{86}$Sr value = 0.706852 ± 0.000045. Isochron $677 \pm 11$ Ma: MSWD = 0.60 and initial $^{87}$Sr/$^{86}$Sr = 0.711258 ± 0.000051. Isochron $394 \pm 12$ Ma: MSWD = 0.29 and initial $^{87}$Sr/$^{86}$Sr = 0.7129 ± 0.0014 (Drake et al., 2017). (b) Isochrons, BSE image and drill core photograph with strike/dip of the illite-epidote and illite-calcite veins indicated, of sample KSH03A:186m. Isochron $393.8 \pm 7.8$ Ma: MSWD = 0.69 and initial $^{87}$Sr/$^{86}$Sr = 0.7100 ± 0.0078. Isochron $357.7 \pm 7.7$ Ma: MSWD = 0.24 and initial $^{87}$Sr/$^{86}$Sr = 0.712188 ± 0.00003. (c) Photograph of drill core of sample KSH03A:197m with vein strike/dip indicated. (d) BSE image of sample KSH03A:197m. (e) Isochron of sample KSH03A:197m. (f) Isochrons of sample KFM06C:391. (g) Isochron of sample KFM06C:391. (h) Thin section microphotograph of sample KFM06C:391. (i) Photograph of drill core of sample KSH03A:225m with vein strike/dip indicated. (j) BSE image of sample KSH03A:225m. (k) Isochron of sample KSH03A:225m. (l) Isochrons of sample KFM04A:306m. Isochron $1,476 \pm 14$ Ma: Initial $^{87}$Sr/$^{86}$Sr = 0.70909 ± 0.00016. Isochron $402 \pm 23$ Ma: Initial $^{87}$Sr/$^{86}$Sr = 0.71636 ± 0.00016. (o) BSE image of petrography for sample KFM06C:391. ab, albite; Adu, adularia; cc, calcite; ms, muscovite.
thickening, as supported by similar models in other cratons (e.g., Uysal et al., 2020).

### 3.3 Poly-phase precipitation processes and gaps of mineralization

The recognized multi-stage discrete mineral growth in eight of 19 samples supports that fluid migration reutilized pre-existing crustal structures. This ratio of reactivated samples to new structures is a minimum due to the potential to detect more reactivation episodes with lower error margins and extended sampling along and across fracturing planes. Common textural and geochronological preservation of older features suggests that overprinting is far from complete. Furthermore, several samples contain poly-phase crystal growth zones in single grains with up to ~1,074 ± 30 Ma age gaps, whereas the smallest gap between growth zones is ~36 ± 15 Ma. This suggests rapid episodic mineralization in response to tectonically initiated fracture reactivation and fluid infiltration pulses. Absence of ages thus indicates long periods when tectonic and/or fluid conditions required for mineral precipitation were not met.

Isotopic resetting and neocrystallization of illite are known to occur during fault propagation and fluid pervasion (Duvall et al., 2011). However, the clear temporal distinction of two precipitation episodes in the illite vein at Laxemar (Figure 3b) evidences that detrital and authigenic clay mineral generations can form intergrowths that are distinguishable by micro-scale in situ dating. Moreover, the temporal correlation of reactivation in shear zones and vein mineralization in discrete fracture networks imply that far-field tectonic events not only affected established shear zones but also caused formation of new fracture sets in the crystalline basement, which has implications for seismic predictions.

### 4 Conclusions and implications

We present direct and absolute Rb-Sr geochronology constraints of petrographically well-characterized vein mineralization that discern fracture reactivation populations at 1,757 ± 15, 1,680 ± 43–1,670 ± 100, 1,495 ± 55–1,429 ± 18, 1,299 ± 36, 1,123 ± 16, 681 ± 21–677 ± 11, 447 ± 37–444 ± 12, 402 ± 23–387 ± 10 and 358 ± 8–355 ± 12 Ma within the Fennoscandian shield. Mesoproterozoic ages related to the Danopolitan-Hallandian Orogeny were the most common, but age clusters linked to the Sveconorwegian and Caledonian Orogens and their subsequent foreland basins were also documented. Clustering of ages from three geographically separated sites allow craton-scale interpretation of far-field tectonic influence. Linkage of mineral age clusters to vein orientations has implications in tectonic reconstructions of cratons in general.

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**FIGURE 4** Timeline displaying age brackets (including uncertainties) of Rb-Sr data for vein and fracture mineral assemblages in Laxemar, Forsmark and Siljan. Literature data are indicated in the figure accordingly: 1Drake et al. (2009); 2Drake et al. (2017); 3Drake, Whitehouse, et al. (2018); 4Sandström et al. (2009); 5Drake, Ivarsson, et al. (2018); 6Tillberg et al. (2019); 7Tillberg et al. (2020). Orogens having affected southern Scandinavia in the Proterozoic (Roberts & Slagstad, 2015) and the Palaeozoic (Roberts, 2003) are plotted. Grey vertically extending bars mark major regional deformation and mineralization events detected in this study. Cld, Caledonian; D-H, Danopolitan-Hallandian; Got, Gothian; SvF, Svecofennian; SvN, Sveconorwegian; TIB, Transscandinavian Igneous Belt.
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