The Nolans rare earth element-phosphorus-uranium mineral system: formation and modification over 1800 million years

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Nolans is a rare earth element-phosphorus-uranium (REE-P-U) fluorapatite vein deposit located in the central part of the Aileron Province. The deposit is hosted mostly by the ca 1805 Ma Boothby Orthogneiss, which has been strongly affected by the 1590–1560 Ma, high T-low P Chewings Orogeny (**Figure 1**; Scrimgeour 2013). Three zones are distinguished: Northern, Central and Southeast zones (**Figure 2a**). The Northern and Southeast zones consist of east-east northeast-trending, steeply north-dipping veins and breccia zones (**Figure 2b**); the Central Zone consists of a north-trending, sub-vertical vein/breccia zone. The current mineral resource at Nolans totals 56 Mt grading 2.6% total rare-earth oxides, 12% P_2O_5 and 162 ppm U (0.42 lb/tonne U_3O_8) (Arafura Resources Limited 2015).

This contribution and Huston *et al* (2016) describe the geology and present an evolutionary model for the Northern Zone; Schoneveld *et al* (2015) presents similar information for the Central Zone. Beyer (2017) present descriptions of possibly related REE-bearing apatite and fluorite occurrences elsewhere in the central Aileron Province.

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The Northern Zone at Nolans is dominated by fluorapatite veins that have a moderately complex paragenesis comprising two apparent stages:

1. massive to granular fluorapatite with inclusions of REE silicates, phosphates and (fluoro)carbonates,
2. calcite-allanite with accessory REE-bearing phosphate and (fluoro)carbonate minerals that vein and brecciate the earlier stage (**Figure 3a**).

In some cases, the REE phosphate and (fluoro)carbonate minerals have very delicate textures (**Figure 4**), suggesting that (re)crystallisation of at least some of these minerals post-dated significant deformation. The veins are locally accompanied by narrow, skarn-like (garnet-diopside-amphibole) wall rock alteration zones (**Figures 2b, 3b**). Fluid inclusion studies, combined with oxygen isotope data suggest that the skarn-like alteration assemblages last equilibrated with a saline (23–26 eq wt% NaCl; $\delta^{18}O$ ~ 7–8‰) fluid at ~410°C and, most likely, 130–200 MPa (4.9–7.5 km). As discussed below, these conditions might not reflect the original conditions of mineralisation but rather the effects of post-depositional modifications.

Where primary mineralised fluorapatite veins are close to the surface, dark-coloured supergene fluorapatite replaces cream-coloured hypogene fluorapatite. Much of the original REE content is taken up by cheralite, which can be associated with a kaolinite alteration zone that occurs in the footwall to the veins but does not extend at depth. The kaolinite

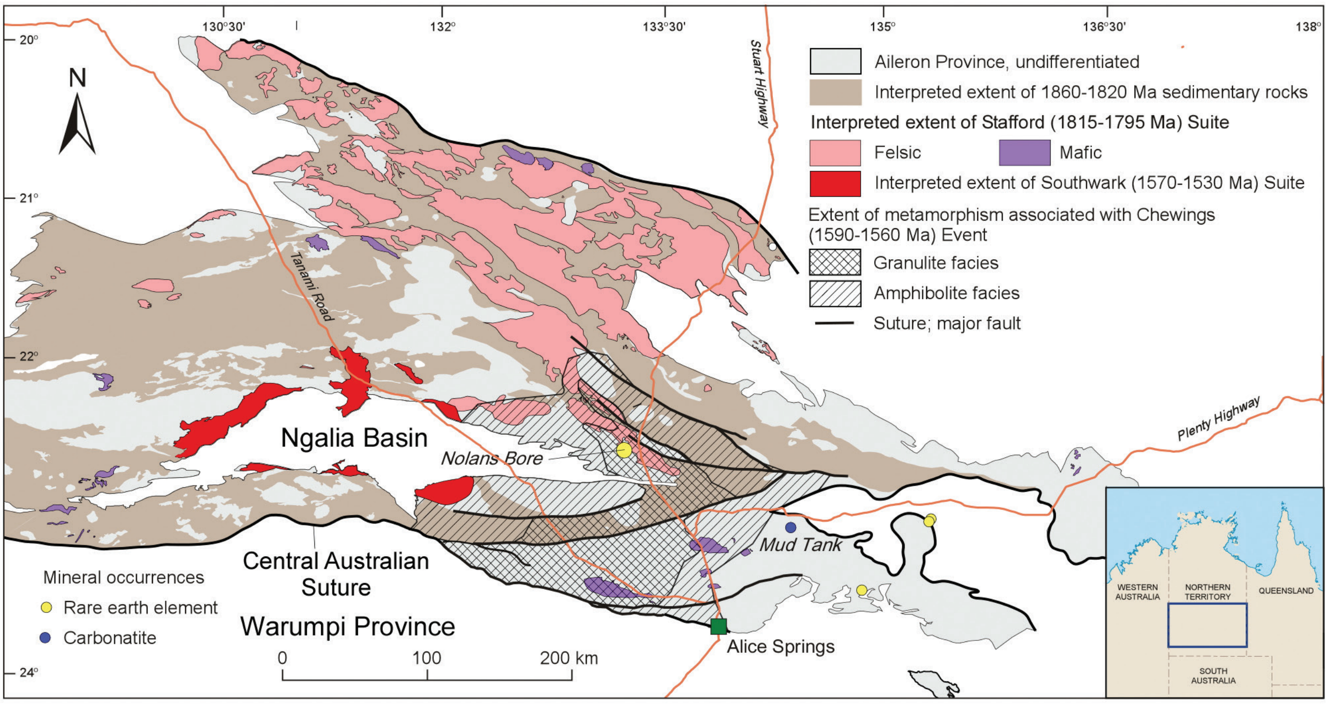

Figure 1. Geology of the Aileron Province showing the location of the Nolans deposit (synthesised from diagrams in Scrimgeour 2013 and Hoatson *et al* 2011).

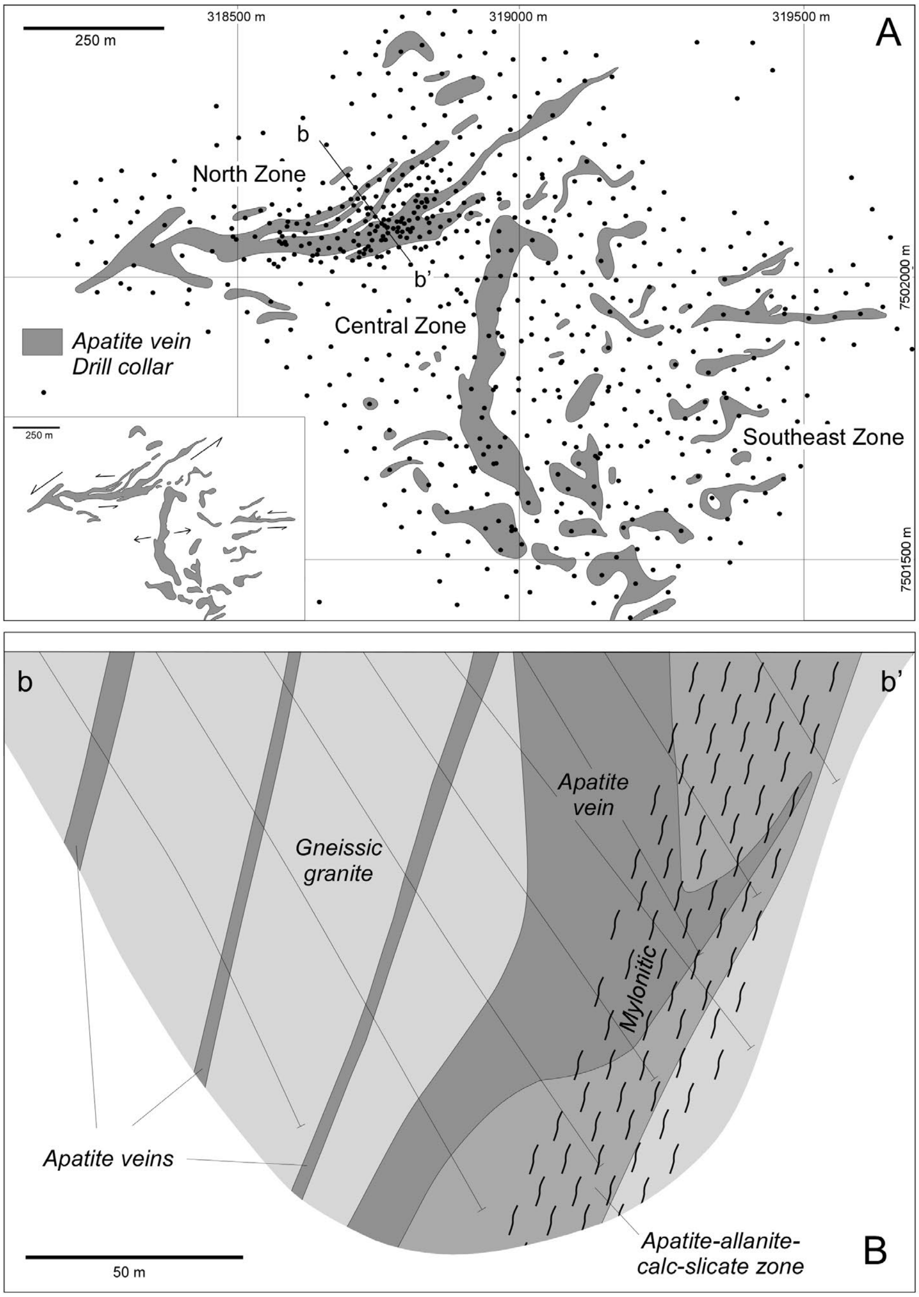

Figure 2. Geology of the Nolans deposit. (**a**) Plan showing the distribution of fluorapatite veins at or near surface. (**b**) Cross-section (see **a** for location) showing the dip of fluorapatite veins and the associated alteration zones. The inset in (**a**) presents a possible structural stress regime to account for the distribution and orientation of the fluorapatite veins.

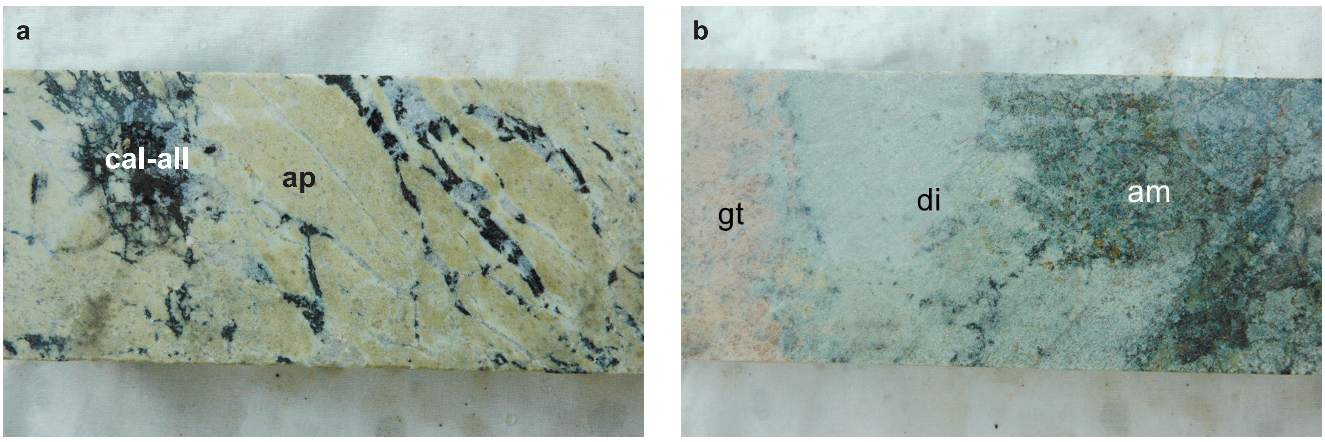

Figure 3. Photographs showing rock types present at Nolans. (**a**) Light cream fluorapatite (ap) vein brecciated and infilled by calcite-allanite (cal-all) veins. (**b**) Diopside-rich alteration assemblage (di) between garnet-rich (gt) and amphibole-rich (am) alteration assemblages. All samples are NQ-size drill core with a width of 47.6 mm.

is interpreted as a weathering product as the presence of kaolinite O-H supports a supergene origin, possibly related to acids released by weathering of fluoroapatite

SHRIMP Th–Pb analyses of allanite yielded an age of 1525 ± 18 Ma (**Figure 5**), interpreted as the minimum age of mineralisation. The maximum age is provided by a ca 1550 Ma SHRIMP U–Pb age of a pegmatite. Other isotopic systems yielded ages from ca 1443 Ma to ca 345 Ma, implying significant post-depositional isotopic disturbance. The observed age decreases with the closure temperature of the isotopic system and/or mineral measured. Variations in Nd and Sr isotopic data can be modelled as mixing between a more primitive ($^{87}Sr/^{86}Sr$ ~ 0.7053, εNd ~ +5) source of the mineralising components with more evolved wall rock, although these modelling results must be treated with caution as post-depositional disturbance is likely.

The complex and somewhat contradictory results presented above suggest that the Nolans deposit records several post-depositional events, spread over 1200 million years (**Figure 6**). Processes leading to formation of

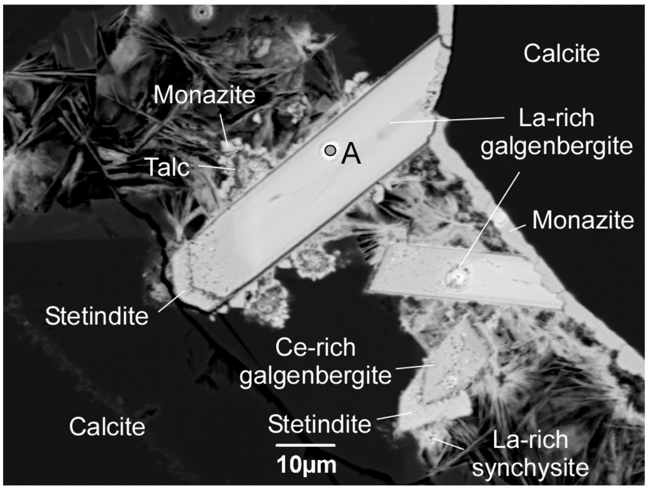

Figure 4. Backscatter electron image showing complex paragenesis within calcite-allanite veins. Monazite overgrows a calcite substrate in the upper right. The monazite is overgrown in apparent paragenetic order as follows La-rich galgenbergite → an assemblage including Ce-rich galgenbergite, stetindite and talc → monazite (?) → La-rich synchesite → calcite.

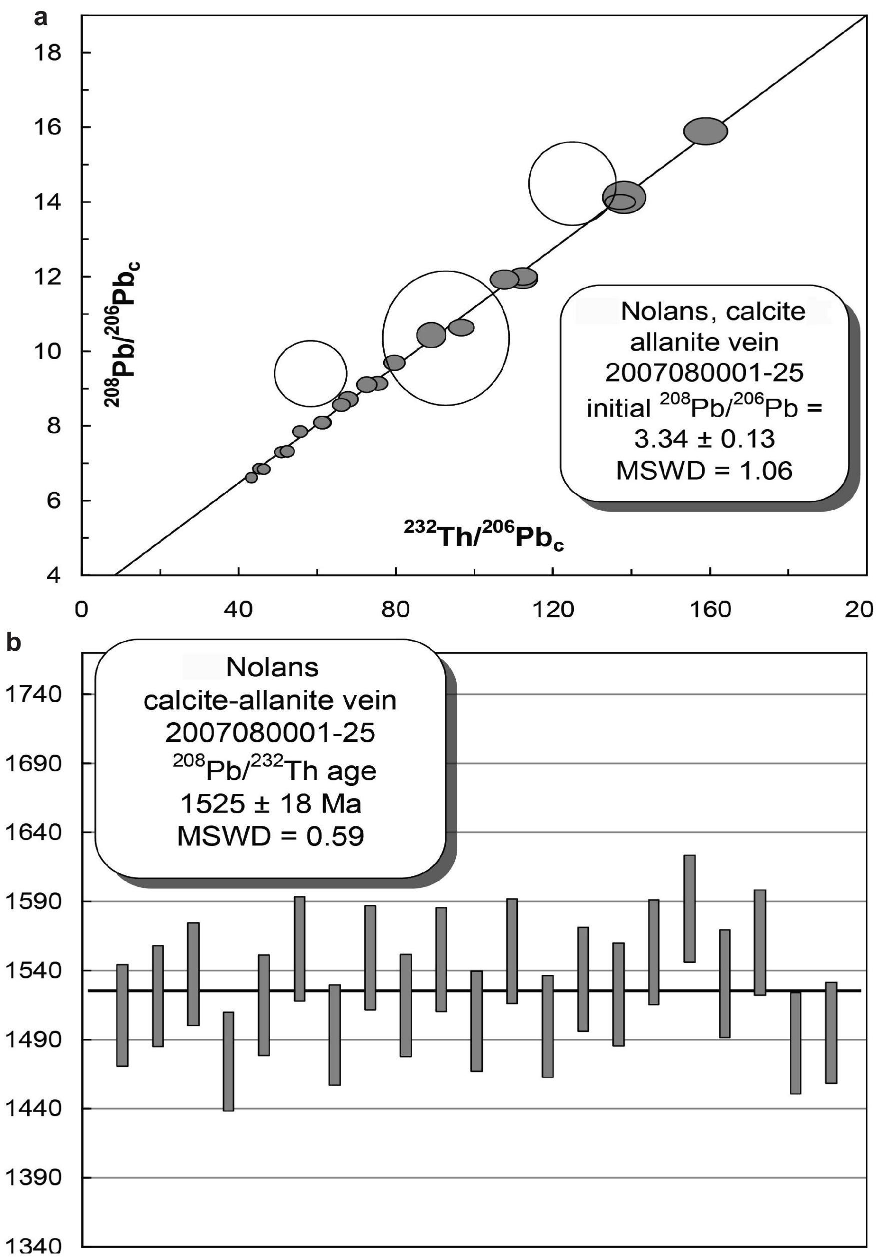

Figure 5. (**a**) $^{232}Th/^{206}Pb$ versus $^{208}Pb/^{206}Pb$ plot for SHRIMP analyses of allanite from sample 2007080001-25. (**b**) $^{208}Pb/^{232}Th$ ages for allanite in order of analysis. The grey bars are 1σ error bars and the heavy black line indicates the weighted mean $^{208}Pb/^{232}Th$ age.

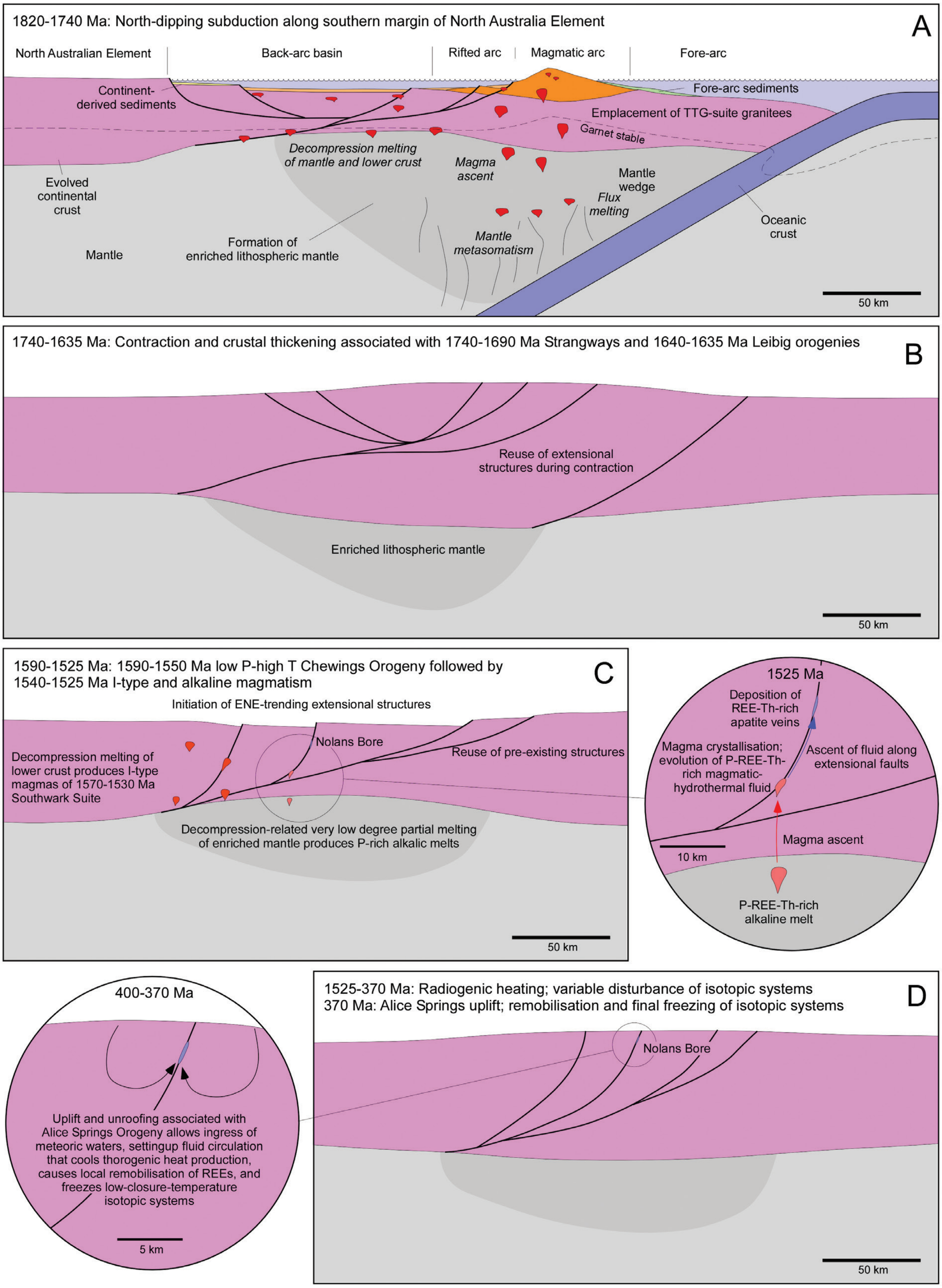

Figure 6. Schematic diagrams showing the evolution of the Nolans mineral system. (**a**) North-dipping subduction associated with convergence along the southern margin of North Australian Element between 1820 and 1750 Ma sets up architecture that controls later fluid movement and metasomatically enriches the mantle wedge. (**b**) Crustal thickening associated with the ca 1740–1690 Ma Strangways and ca 1635 Ma Leibig orogenies. (**c**) Melting of enriched mantle wedge initiates towards the end of the Chewings Orogeny, producing alkaline magmas melts that move along reactivated structures into mid- to upper-crust where a phosphate-rich magmatic-hydrothermal fluid and/or immiscible melt separates. Fluorapatite and REE minerals are precipitated in veins and breccias as a consequence of physicochemical changes caused by cooling and/or reaction with wall rocks. (**d**) Uplift associated with later movements of Alice Springs Orogeny unroofs Nolans deposit. Weathering of fluorapatite produces highly acidic and corrosive fluids than mobilise REE and re-deposit them in kaolinitised wall rocks as the fluids are neutralised.

Nolans are interpreted to have begun with north-dipping subduction along the south margin of the Aileron Province at ca 1820–1750 Ma (**Figure 6a**), producing a metasomatised, volatile-rich lithosphere. About 200 million years later, during the latter stages of, or just after, the Chewings Orogeny, this reservoir and/or the lower crust sourced low-degree, alkaline partial melts that passed into the mid- to upper-crust (**Figure 6c**). Although the exact mechanisms of mineral deposition are not clear, fluids derived from these melts, which may have included phosphatic melts, eventually deposited the Nolans fluorapatite veins due to fluid-rock interaction, cooling, depressurisation and/or fluid mixing.

Owing to its size and high concentration of Th (2500 ppm), *in situ* radiogenic heating within the Nolans mineralised zone caused significant recrystallisation and isotopic resetting. The system finally cooled below 300°C at ca 370 Ma, possibly in response to unroofing during the Alice Springs Orogeny (**Figure 6d**). During this time, the Central Zone may have formed by the remobilisation of pre-existing mineralisation in response to the influx of heated meteoric or other waters (*cf* Schoneveld *et al* 2015). Surface exposure and weathering of fluorapatite produced acidic fluids and near-surface, intense kaolinitised zones that include high-grade, supergene-enriched cheralite-rich mineralisation.

Beyer (2017) documents the presence of biotite schist hosted by the ca 1777 Ma (Beyer *et al* 2015) Wangala and ca 1621 Ma (Kositcin *et al* 2013) Ennungan Mountain granites. She interprets these biotite schist units as hydrothermal alteration zones that overprint the respective granites at ca 1575 Ma. The biotite schist units in both Wangala and Ennungan Mountain granites are enriched in REE, P, U, F and a suite of other elements. They also have a northeast trend (E Beyer pers comm 2017), broadly similar to the east-northeast trend observed at Nolans. In addition, the biotite schist at the Wangala Granite contains up to 25% apatite. The data of Beyer (2017) and the data from Nolans both point to a single or a series of closely spaced hydrothermal REE-P-U events in the central Aileron Province towards the end of the Chewings Orogeny, possibly associated with east-northeast to northeast-trending structures/fabrics.

The total possible age range of the central Aileron hydrothermal events (1575–1525 Ma) overlaps with the age ranges of iron oxide copper-gold (IOCG) events (1595–1565 Ma and 1525–1475 Ma: Mark *et al* 2004, Duncan *et al* 2011) in the Cloncurry (Queensland) district in the eastern part of the North Australian Craton. Although the Cloncurry events were dominated by introduction of Cu and Au, they also involved the introduction of U, REE, F and other elements (eg Ernest Henry deposit: Ryan 1998). These data may indicate that the central Aileron REE-P-U-Th mineralising event may be part of a much larger system that has affected the North Australian Craton more broadly.

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