Supplementary Data File for article

Uncharted Permian to Jurassic continental deposits in the far north of Victoria Land, East Antarctica

by

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containing

Fig. S5. Results of X-Ray Diffractometry analyses for three sandstone samples from the Van der Hoeven Formation (sample NVL1116, HCCL section) and the Helliwell Formation (samples NVL116 and NVL216, HCSE section) in the Helliwell Hills, lower Rennick Glacier, northern Victoria Land, East Antarctica.

Fig. S6. Binary discrimination plot after Roser and Korsch (1986) for three sandstone samples from the Van der Hoeven Formation (NVL1116) and Helliwell Formation (NVL116 and NVL216), northern Victoria Land, East Antarctica.

Fig. S7. Trace-element concentration plots ('spider plots') for three sandstone samples from the Van der Hoeven Formation (NVL1116) and Helliwell Formation (NVL116 and NVL216), northern Victoria Land, East Antarctica.

Supplementary references

Fieldwork details

Field work in the remote Helliwell Hills region (Fig. 1) was carried out in the course of a joint project of the Italian, German, and Korean Antarctic research programmes. The Helliwell Hills camp was installed and first used by a field team of the Italian Antarctic Research Programme (Programma Nazionale di Ricerche in Antartide, PNRA) during the austral summer 2014-2015. The camp was then sealed overwinter and used again the following season; first during the third Korean Antarctic Geological Expedition (KAGEX III) from 12–28 Dec 2015, then by the joint German-Italian Research Programme of the 11th German Antarctic North Victoria Land Expedition (GANOVEX XI) from 6–28 Jan 2016. Overall fair weather conditions during this latter period allowed the first two authors to work afoot for eleven days in the immediate surroundings of the camp area, usually upslope along the eastern flanks of an unnamed small mesa at the northern end of the Helliwell Hills. Additional six days with helicopter support were used to visit other sections in the area north of Mount Van der Hoeven, at an unnamed ridge in the central Helliwell Hills area, and around Boggs Valley.

Palynological processing

Depending on grain size and organic content, between 5 to 10 g of each sample were treated with hydrofluoric acid (48% HF at room temperature) for two to three days until the mineral matrix was sufficiently dissolved. Samples were then neutralized without centrifuging, i.e., by repeated steps of adding distilled water and careful decanting once residues had settled. Sample pH thus approached neutral after four to five rinses. The organic residues were then macerated using Schulze's reagent [nitric acid (HNO3 in concentrations varying between 25% and 65%, depending on sample maturity) with a few crystals of potassium chlorate (KClO3)], cleaned and bleached using 10% potassium hydroxide (KOH) for a few seconds, and then sieved over 250 µm and 10 µm mesh screens; sodium polytungstate with a density of d = 2.0 was used for the following density separation of the 10–250-µm-size fraction. Glycerine jelly was used as the mounting medium for the preparation of permanent slides for light-microscopical analysis.

Quantitative mineralogical and bulk-rock geochemical analyses

Methods.—Three samples (NVL1116, NVL116, and NVL216) were analysed at the German Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe, BGR), Hannover, for petrography and via X-ray powder diffraction (XRD) for qualitative mineralogical composition using a Philips/PANalytical X'Pert Pro-MPD Powder Diffractometer (Co-Kα radiation generated at 40 kV and 40 mA), equipped with a variable divergence slit (20 mm irradiated length), primary and secondary soller, Scientific X´Celerator detector (active length 2.122°), and a sample changer (sample diameter 28 mm). The samples were investigated from 2° to 85° 2Θ with a step size of 0.0167° 2Θ and a total measuring time of 67 min. The back-loading technique was used for specimen preparation.

In addition, major and trace elements of samples NVL1116, NVL116, and NVL216 were detected via X-ray fluorescence (XRF) at the BGR and by Activation Laboratories Ltd. (Actlabs), Ancaster, Canada, using the lithium metaborate/tetraborate fusion ICP-MS method (code 4B2 Research). XRF analysis was performed at the BGR using a PANalytical Zetium Wavelength Dispersive X-ray Fluorescence Spectrometer with Rh tube. Loss on ignition (LOI) was determined by heating the sample powder to 1030 °C for 10 min. For ICP-MS analysis by Actlabs, the fused and diluted samples were analyzed using a Perkin Elmer Sciex ELAN Inductively Coupled Mass Spectrometer (ICP-MS). For the fusion process, the sample powder is mixed with lithium metaborate and lithium tetraborate in graphite crucibles and fused in induction furnaces at 1150 °C. Further analytical details and detection limits are available from the Actlabs website (http://www.actlabs.com). Plots were performed by using the GeoChemical Data toolkit (GCDkit; Janoušek *et al.* 2006).

Results and discussion.—Results of X-ray diffraction analyses (Fig. S5) confirm that sample NVL1116 from the lower new unit at the Helliwell Hills HCCL section is dominated by quartz, with only accessory feldspar (albite and orthoclase), chlorite, and muscovite/illite. Sandstone samples NVL116 and NVL216 from the middle portion (HCSE07) of the upper new unit at the Helliwell Hills section are, by contrast, composed of quartz, feldspar (albite and orthoclase), and heulandite, with accessory chlorite, muscovite/illite, and additional zeolites (laumontite and stilbite) (Fig. S5), indicating abundant weathering products of volcanogenic material.

In the binary tectonic discrimination plot following Roser and Korsch (1986), the high quartz content of sample NVL 1116 suggests a passive margin tectonic setting, whereas the high input of volcanogenic detritus in samples NVL 116 and NVL 216 leads to an active continental margin setting (Fig. S6). Trace element concentrations were plotted in multi-element (spider) diagrams normalized to upper continental crust (UCC; Taylor and McLennan 1995) and REE chondrite (Nakamura 1974) (Fig. S7). If compared to UCC, all three samples show negative anomalies in Rb, K, Nb, Ta, Sr and P. Compared to samples NVL 116 and NVL 216, however, sample NVL 1116 is slightly depleted in Ba and strongly in Sr and P, but enriched in Th, U, La, Ce, Hf, Zr, Sm and Ti (Fig. S7). In the REE chondrite-normalized plot, NVL 1116 differs from the other two particularly in higher contents of LREE with slightly depleted Eu (and thus a stronger LREE slope), whereas HREE concentrations are relatively similar in all three samples (with a moderate slope); all three samples show a slightly negative Eu anomaly (Fig. S7). The same enrichment of LREE of NVL 1116 is visible in the UCC-normalized multi-element plot with concentrations higher than the average upper continental crust. The REE patterns generally suggest a dominance of more felsic rocks rather than mafic/ultramafic rocks in the source area of the analysed samples. This is further supported by the rather low Cr/V ratio in these samples, as well as enrichment in Zr and Hf particularly in NVL 1116 pointing to a possibly more mature continental crust component in this sample.

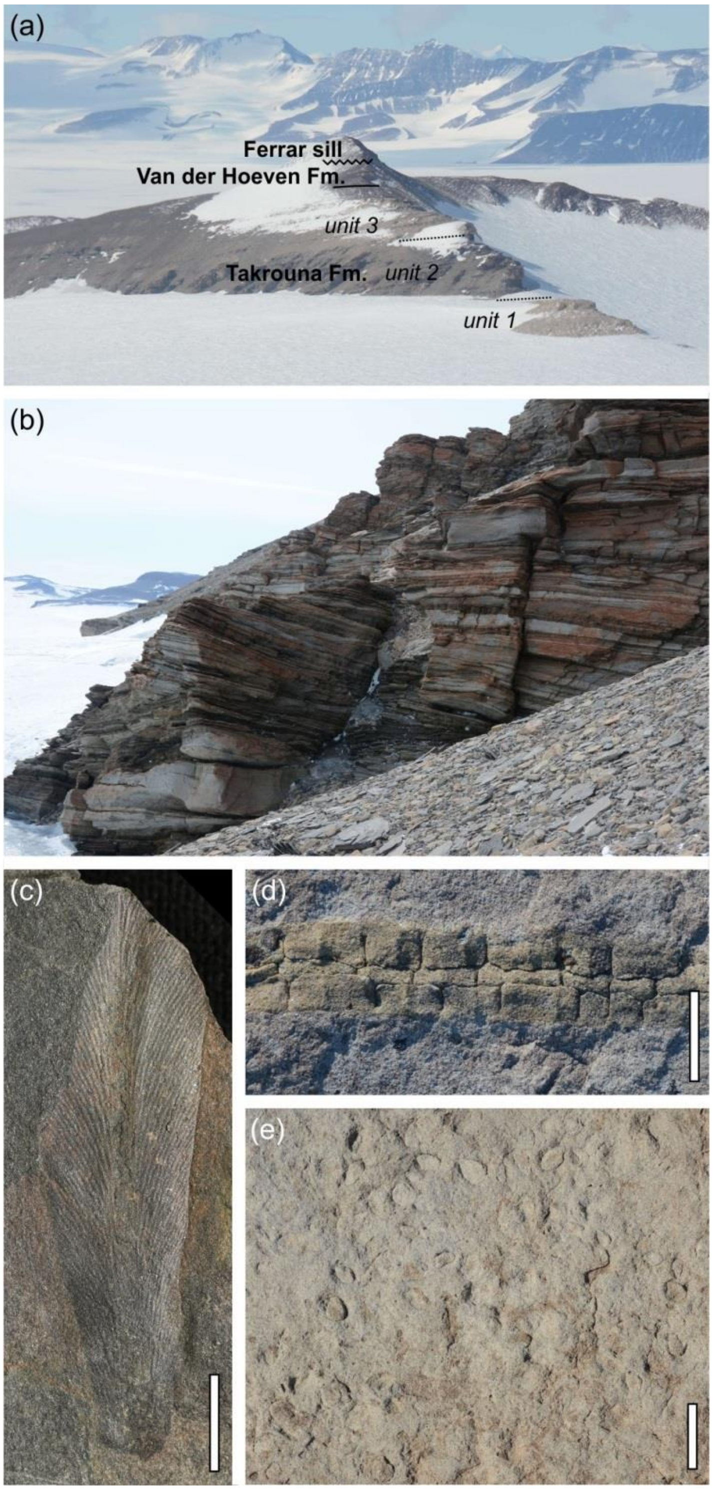

Fig. S1. Field images and fossil content of the Permian Takrouna Formation in the Helliwell Hills, northern Victoria Land. (**a**) View northeast to a ~140-m-thick section (BS) at an unnamed nunatak about halfway between Mount Remington and Mount Bresnahan; (**b**) detail showing a succession of heterolithic sandstone, ripple-laminated sand- and siltstone, and carbonaceous mudstone in the middle part [unit 2 in (a)] of the BS section; (**c**) *Glossopteris* sp. leaf from the lower part of the Takrouna Formation at Boggs Valley; (**d**) characteristically chambered *Vertebraria indica* (glossopterid root) from the upper part [unit 3 in (a)] of the Takrouna Formation at the BS section; (**e**) *Lockeia* sp. trace fossils from the upper part [unit 3 in (a)] of the Takrouna Formation at the BS section. Scale bars: (c) = 1 cm, (d, e) = 2 cm.

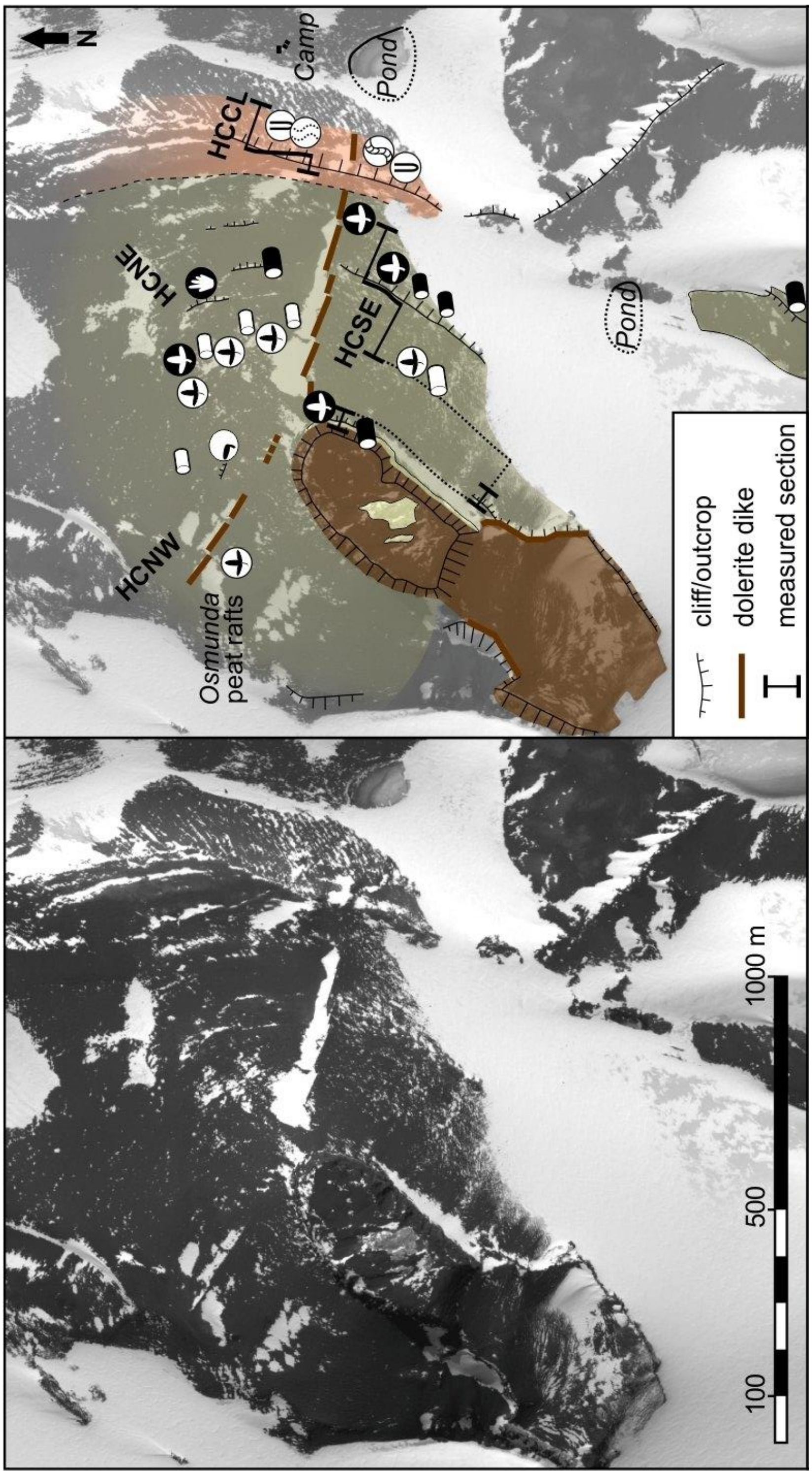

Fig. S2. Satellite images of the type section of the Helliwell Formation and nearby exposures surrounding an unnamed mesa 3 km east of Dziura Nunatak in the northern Helliwell Hills, showing stratigraphic units, measured sections, and important macro- and microfossil sites. Satellite image courtesy of the DigitalGlobe Foundation. See Fig. 3 for legend.

Fig. S3. Field images of the Section Peak Formation exposed immediately below and on top of a cliff-forming sill at an unnamed mesa 3 km east of Dziura Nunatak in the northern Helliwell Hills, northern Victoria Land. (**a**) pebbly coarse-grained sandstone at the base of the formation, with a garnet-rich lag layer (arrow); (**b**) detail of lag layer in (a) showing sand-sized garnet clasts; (**c**) erosional remnants of the Section Peak Formation on top of the mesa-forming sill at the HCtop section (person for scale); (**d**) detail showing an erosional channel fill of mid- to coarse-grained sandstone with imbricated mudstone clasts (arrows) at the base; (**e**) mudstone intraclast sampled for palynological analysis.

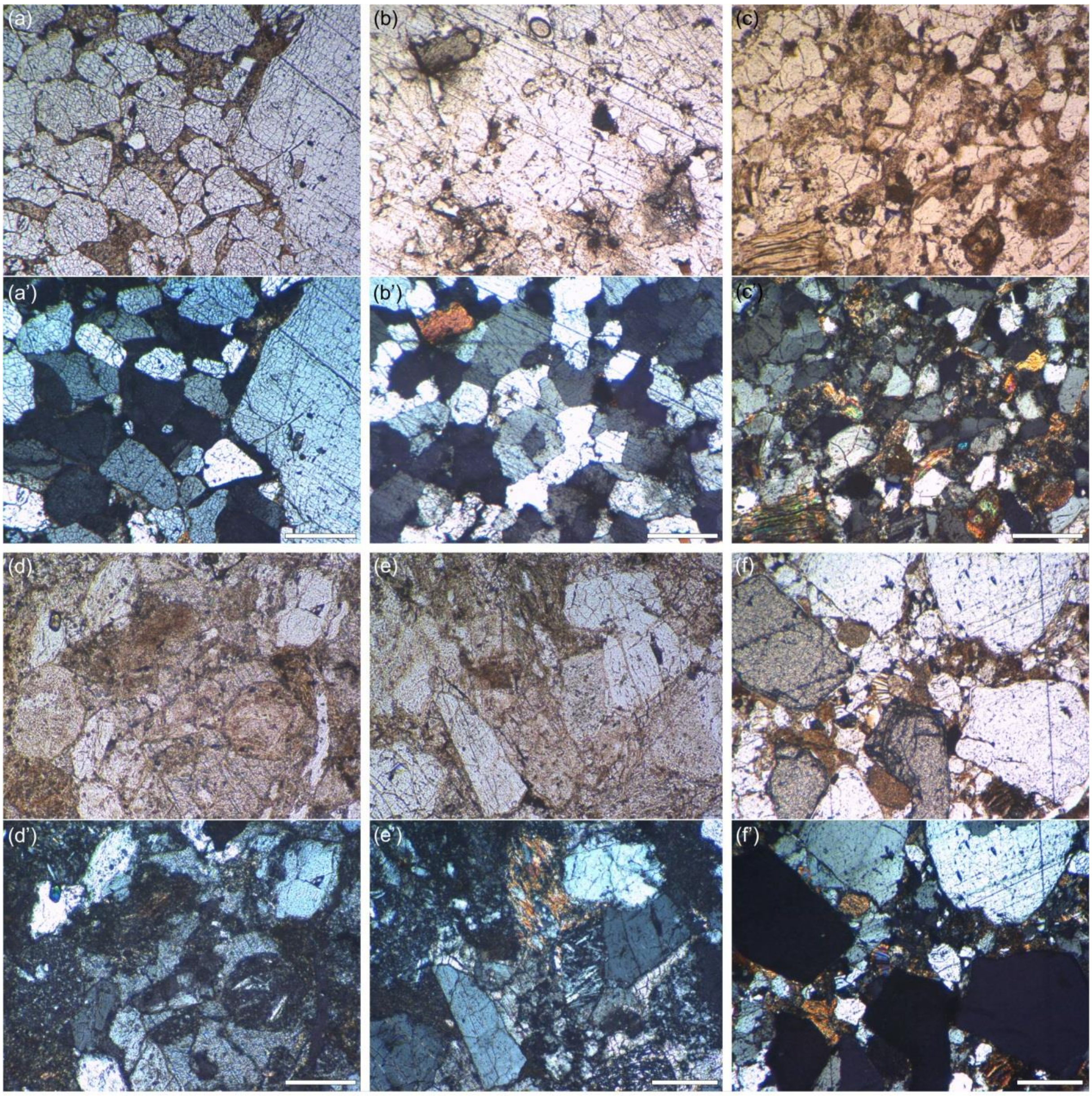

Fig. S4. Petrography of selected sandstone samples from the Van der Hoeven Formation (a–c), Helliwell Formation (d, e), and Section Peak Formation (f) in the Helliwell Hills, lower Rennick Glacier. (**a**) coarse-grained subarkose (bed BS10) from the base of the Van der Hoeven Formation at the BS section half-way between Mount Remington and Mount Bresnahan; (**b**) medium-grained quartzarenite from the BVM section at an unnamed, isolated nunatak west of the Boggs Valley; (**c**) fine-grained subarkose (bed HCCL09) from the top of the Van der Hoeven Formation at the HCCL section in the northern Helliwell Hills; (**d**) fine-grained volcaniclastic litharenite (bed HCSE05) from the basal part of the Helliwell Formation at the type section; (**e**) fine- to medium-grained lithic arkose (bed HCSE07) from the basal part of the Helliwell Formation at the type section; (**f**) coarse- to very coarse-grained subarkose with abundant garnet (bed HCSE12) from the base of the Section Peak Formation at the HCSE section in the northern Helliwell Hills. Scale bars: (a, b, f) = 500 µm, (c–e) = 200 µm.

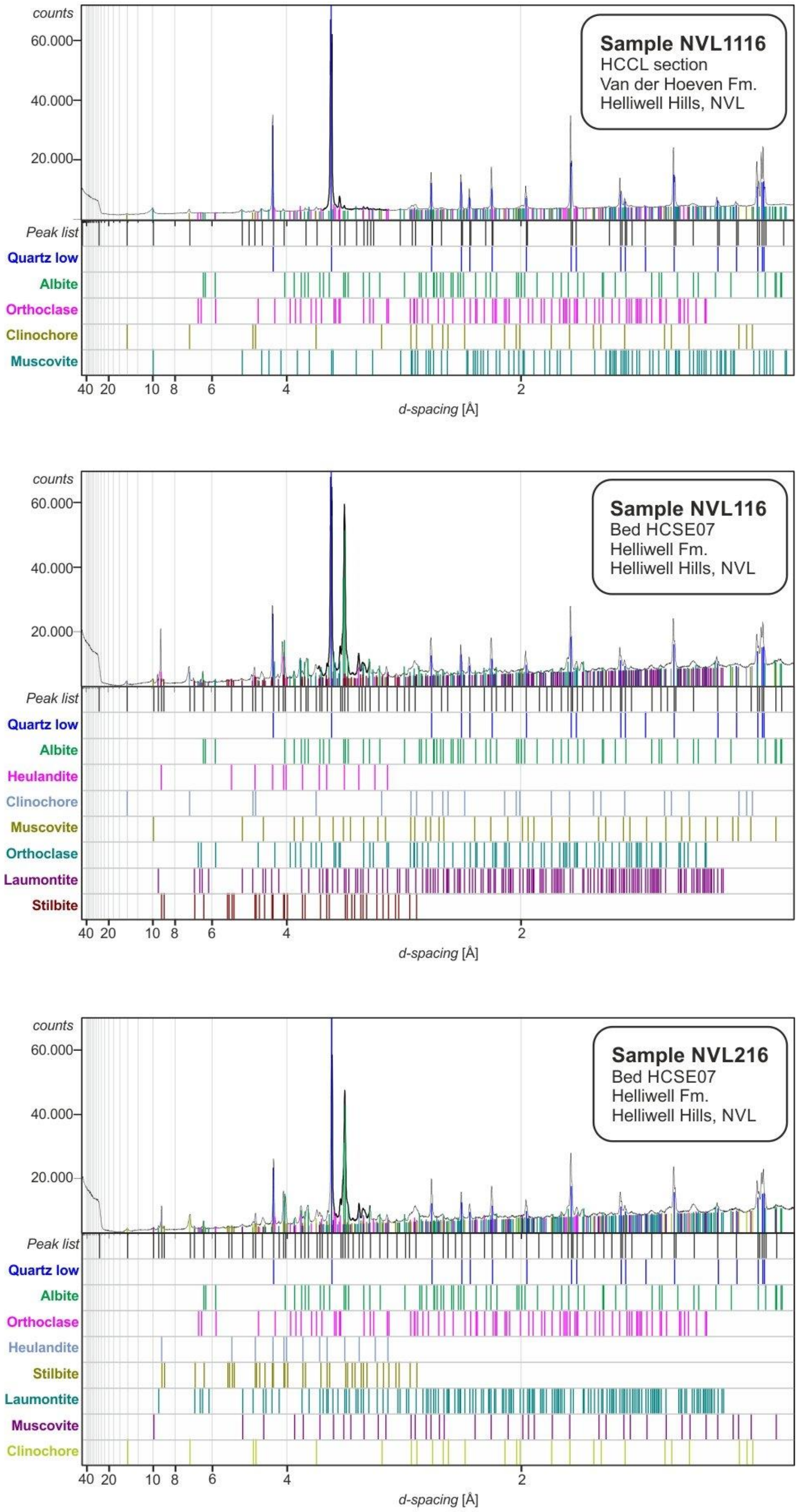

Fig. S5. Results of X-Ray Diffractometry analyses for three sandstone samples from the Van der Hoeven Formation (sample NVL1116, HCCL section) and the Helliwell Formation (samples NVL116 and NVL216, HCSE section) in the Helliwell Hills, lower Rennick Glacier, northern Victoria Land, East Antarctica.

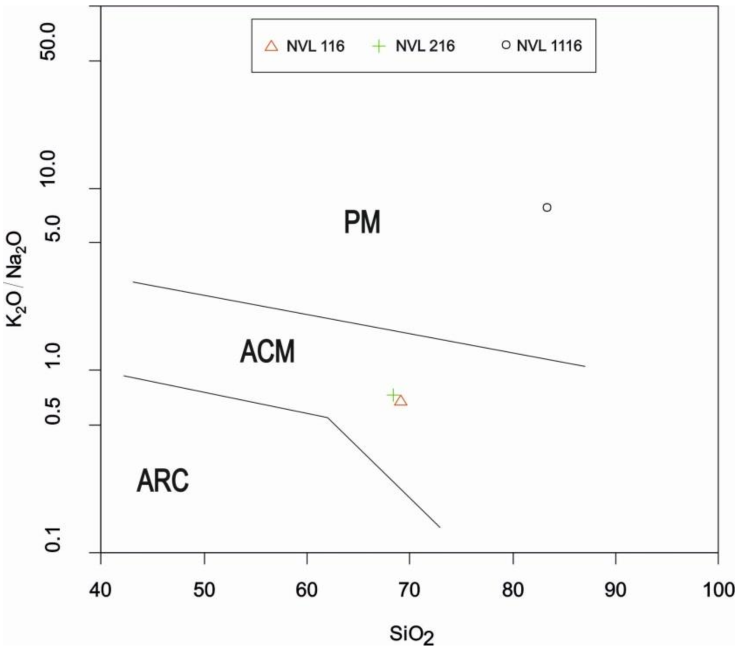

Fig. S6. Binary discrimination plot after Roser and Korsch (1986) for three sandstone samples from the Van der Hoeven Formation (NVL1116) and Helliwell Formation (NVL116 and NVL216), northern Victoria Land, East Antarctica; ARC = oceanic island-arc setting; ACM = active-continental-margin setting; PM = passive-margin setting.

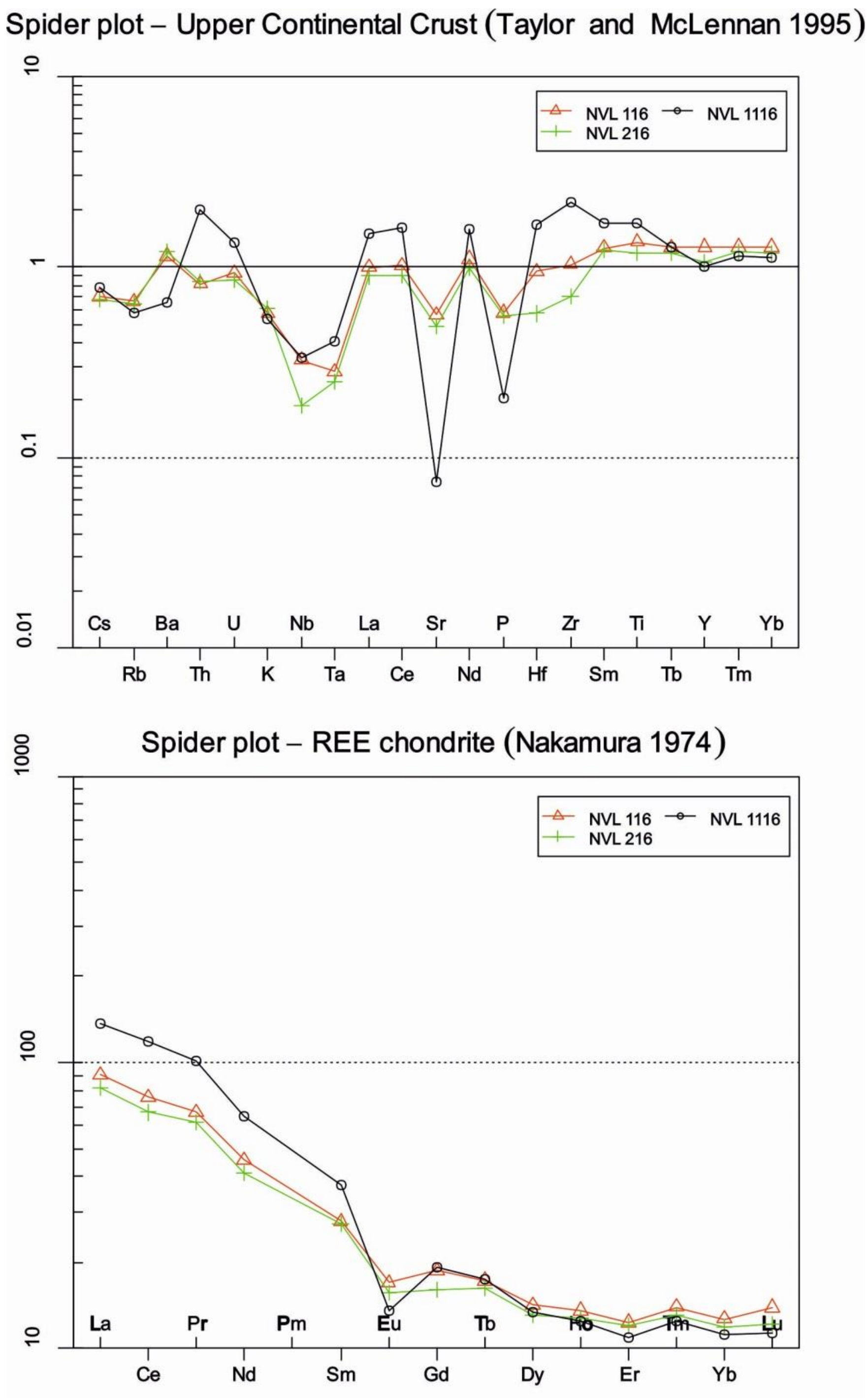

Fig. S7. Trace-element concentration plots for three sandstone samples from the Van der Hoeven Formation (NVL1116) and Helliwell Formation (NVL116 and NVL216), northern Victoria Land, East Antarctica.

Supplementary References

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