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► **To cite this version:**

Tu-Han Luu, Pamela Gutiérrez, Edward C Inglis, Catherine Chauvel, Daniel J. Roberts. HIGH-PRECISION SR AND ND ISOTOPE MEASUREMENTS USING A DYNAMIC ZOOM LENS-EQUIPPED THERMAL IONISATION MASS SPECTROMETER. *Chemical Geology*, 2022, 10.1016/j.chemgeo.2022.121078 . hal-03761496

HAL Id: hal-03761496

<https://hal.science/hal-03761496v1>

Submitted on 26 Aug 2022

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1 HIGH-PRECISION SR AND ND ISOTOPE MEASUREMENTS USING A DYNAMIC ZOOM
2 LENS-EQUIPPED THERMAL IONISATION MASS SPECTROMETER
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15 **Keywords**

16 Nu TIMS, high precision Sr isotopic measurements, high precision Nd isotopic measurements
17

18 **Significant statement**

19 High precision Sr and Nd isotopic measurements are of key importance in the field of
20 Earth Sciences because they are powerful tools to trace sources of materials and to date them.
21 Here, we report the first high-precision data for ⁸⁷Sr/⁸⁶Sr and ¹⁴³Nd/¹⁴⁴Nd (external error of 5-6
22 ppm for Sr and 4-5 ppm for Nd) measured using a Nu Instruments TIMS. Such precisions will
23 open new opportunities in fields such as geochemistry, geochronology, cosmochemistry,
24 archaeology or forensics.
25

26 **Abstract**

27 Techniques for the determination of radiogenic strontium (⁸⁷Sr/⁸⁶Sr) and neodymium
28 (¹⁴³Nd/¹⁴⁴Nd) isotope ratios by Thermal Ionisation Mass Spectrometry (TIMS) are presented in
29 this study. We have developed a 5 lines acquisition routine for both elements, taking advantage
30 of the 16 Faraday cups available on the Nu Instruments TIMS in conjunction with an efficient
31 zoom lens system. This allows increased flexibility regarding the number of lines in a
32 multidynamic acquisition routine whilst maintaining optimal peak alignment and peak shape
33 for every measurement line despite the fact that the detectors are not movable. The long-term
34 reproducibility obtained for our Sr (NBS 987) and Nd (Rennes-Ames) standard solutions gives
35 a (⁸⁷Sr/⁸⁶Sr)_{multidyn} of 0.7102467 ± 0.0000043 (6.0 ppm, 2 s.d., n = 38) and a (¹⁴³Nd/¹⁴⁴Nd)_{multidyn}
36 of 0.5119537 ± 0.0000022 (4.2 ppm, 2 s.d., n = 31), respectively. We also report
37 (⁸⁷Sr/⁸⁶Sr)_{multidyn} and (¹⁴³Nd/¹⁴⁴Nd)_{multidyn} for a set of terrestrial rock standards (including 5
38 basalts (BCR-2, BHVO-2, BIR-1, Be-N and BR-24), one rhyolite (RGM-1) and one andesite
39 (AGV-2)) with the same, or greater, level of precision as for the pure standards solutions. This
40 level of precision is 2 to 3 times better than the literature data for Sr isotope ratios, and
41 comparable to the latest high precision data reported for Nd isotope ratios. This is the first paper
42 reporting such high precisions for radiogenic Sr and Nd data generated using a TIMS from Nu
43 Instruments.

44 1. Introduction

45

46 Isotope geochemistry has been widely used to probe the evolution and heterogeneity of the
47 terrestrial mantle (e.g., White 2015). Among the different tools available, radiogenic isotopes
48 are of particular interest because (i) they are not directly fractionated by magmatic processes
49 and thus are good source tracers, and (ii) they give information about the timing of processes
50 *via* their parent-to-daughter decay ratios being time-integrated over the entire history of the
51 Earth. A large number of isotope systems are available, but the most extensively used are the
52 incompatible lithophile element systems: ^{87}Rb - ^{87}Sr (half-life of 49.23 Ga), ^{147}Sm - ^{143}Nd (half-
53 life of 106 Ga), ^{176}Lu - ^{176}Hf (half-life of 3.86 Ga), ^{138}La - ^{138}Ce (half-life of 292.5 Ga), ^{238}U - ^{206}Pb
54 (half-life of 4.47 Ga), ^{235}U - ^{207}Pb (half-life of 0.71 Ga), ^{232}Th - ^{208}Pb (half-life of 14.05 Ga).

55 The ^{87}Rb - ^{87}Sr and ^{147}Sm - ^{143}Nd systems were the first used. A major advantage of these
56 systems is that Rb is more incompatible than Sr while Sm is less incompatible than Nd during
57 partial melting of the mantle. This results in a crust enriched in incompatible elements (high
58 Rb/Sr and low Sm/Nd) and an upper mantle depleted in incompatible elements (low Rb/Sr and
59 high Sm/Nd) after melt extraction. Pioneering work in the 1970s defined the $^{87}\text{Sr}/^{86}\text{Sr}$ and
60 $^{143}\text{Nd}/^{144}\text{Nd}$ mantle array (De Paolo and Wasserburg, 1979), and since then traditional
61 radiogenic (Sr-Nd-Pb) isotope compositions measured in oceanic island basalts (OIBs) around
62 the world have refined the original mantle array to 5 end-member mantle components: DMM
63 (for depleted MORB mantle), HIMU (corresponding to a reservoir with high $^{238}\text{U}/^{204}\text{Pb}$ and
64 often associated with recycling of oceanic crust; Chauvel et al. 1992), EM1 and EM2 (for
65 enriched mantle 1 and 2, which are reservoirs characterized by variable Rb/Sr and low Sm/Nd)
66 and PREMA (for prevalent mantle) also called FOZO or C. Despite this, the exact number of
67 end-member compositions and their nature are still highly debated. Indeed, establishing subtle
68 differences depends on improved precision and accuracy of isotopic measurements.

69 Improvement in analytical techniques over the last years has led to better precisions for
70 isotope measurements: differences of a few parts per million (ppm) can now be detected
71 compared to precisions of the order of tens or hundreds of ppm in the late 1970s. This has
72 allowed the definition of for example distinct parallel trends between EM1 and EM2 mantle
73 end-members in the Ce-Nd isotope space or in the Hf-Nd isotope space (e.g., Doucelance et al.
74 2021; Béguelin et al. 2021), leading to a better constraint on the nature and the age of the
75 recycled material responsible for the extended mantle heterogeneity. Another example of the
76 utility of high precision measurements for radiogenic isotope systems comes from Abouchami
77 et al. (2005) who used high precision Pb isotope data to report, for the first time, different trends
78 between the two chains of Hawaiian volcanoes Loa and Kea, with only very little compositional
79 overlap in their Pb isotope features. This has allowed to better constrain the structure and
80 geometry of the plumes ascending to the surface. Similar fine structures could be found in the
81 Sr-Nd isotopic space with the improvement in precision of Sr and Nd isotope data as reported
82 in our study. Aside from mantle geochemistry, the improvements in analytical protocol have
83 greatly advanced the field of geochronology. For example, the latest high-precision Sm-Nd
84 geochronology data allow for the resolution of ages to a precision of ± 1.0 Ma on very small
85 samples (1-10 ng of Nd; e.g., Starr et al., 2020).

86 In this paper, we demonstrate that the latest generation of thermal ionisation mass
87 spectrometers (TIMS) from Nu Instruments allows precisions of a few ppm to be reached, by

88 taking advantage of the presence of a large number of detectors accompanied by an efficient
89 zoom lens system. As mentioned above, this will have important implications in the field of
90 mantle geochemistry, but not only. Indeed, the Sr and Nd systematics are also powerful tools
91 in fields such as cosmochemistry, archaeology, ocean chemistry or paleoclimatic studies, to
92 only cite a few. Improving the precision on measurements should help establishing small
93 differences in sources or in temporal variations, or it could be a key tool to distinguish minor
94 changes in geological and environmental processes.

97 2. Chemical procedures

99 a. Sample digestion

101 Complete digestion of between 50 mg and 100 mg of rock powder was accomplished using
102 a 3:1 mixture of 28N HF and 16N HNO₃ acids on a hotplate at ~ 120°C for at least two days.
103 The samples were then dried down and redissolved two times with 5 ml of 6N HCl followed
104 by 5ml of 2N HCl to decompose fluorides. The set of rock standards analysed in the course of
105 this study comprises 5 basalts (BCR-2, BHVO-2, BIR-1, Be-N and BR-24), one rhyolite (RGM-
106 1) and one andesite (AGV-2) to encompass a wide range of geological matrices.

108 b. Separation of strontium and neodymium

110 The Sr and Nd chemical separations were achieved in a two-step chromatographic
111 procedure adapted from the one published in Chauvel et al. (2011). The first step, common to
112 both elements, corresponds to a cation-exchange chromatography in HCl on a BioRad PolyPrep
113 column filled with 2 ml of AG50W-X8 resin (200-400 mesh). This step allows the removal of
114 major elements, while collecting the Sr fraction in 3.5N HCl and the LREE fraction in 6N HCl.
115 From there, the Sr fraction was further purified using a small (~ 3 mm diameter) homemade
116 shrink fit Teflon column filled with ~ 0.4 mL of Sr-spec resin (50-100 µm). Rubidium, and its
117 interfering ⁸⁷Rb isotope, was removed using 3N HNO₃ and Sr was collected in ultrapure Milli-
118 Q® water (18.2 MΩ.cm). On the other hand, the LREE fraction was further purified using a
119 plastic column (~ 7 mm diameter) filled with ~ 1 mL of Ln-spec resin (50-100 µm). During this
120 step, the Nd fraction is collected in 0.25N HCl, allowing to separate it from Sm, the main
121 interfering species when measuring ¹⁴³Nd/¹⁴⁴Nd. Our chemical procedures give a total
122 procedural blank of ~ 100 pg for Sr and ~ 25 pg for Nd.

123 Following the Sr and Nd chemical separations, we systematically analysed an aliquot of 5%
124 of each processed sample on an Agilent 8900 triple quadrupole ICP-MS at the Institut de
125 Physique du Globe de Paris. This allows for the determination of the Sr and Nd recoveries, but
126 also to ensure that no residual trace of Rb and Sm is present in the Sr and Nd fractions that will
127 be loaded on filaments. Strontium and Nd recoveries were > 75% and > 85% respectively,
128 giving on average more than 20 µg Sr and more than 1.5 µg Nd subsequently available for
129 analysis, with typically Rb/Sr < 1×10⁻⁵ and Sm/Nd < 6×10⁻⁵, for all the rock standards.

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3. Strontium and neodymium isotope measurements by Nu TIMS

a. Generalities

Strontium and neodymium isotopes are generally measured in static mode (on both TIMS and MC-ICPMS), with all the ion beams acquired simultaneously. This configuration is easier to set up on a mass spectrometer, does not necessitate a large number of detectors, and provide isotopic results precise enough when looking at variability between samples of the order of tens of ppm or more. However, when higher precision data is required, isotope measurements in a dynamic mode allow to better compensate for the relative deterioration of the Faraday detectors and their change in efficiency with time, and thus return more accurate isotopic results (e.g., Avanzinelli et al. 2005, Henshall et al. 2018, Fukai et al. 2017).

A Nu TIMS was installed at the Institut de Physique du Globe de Paris early 2020 (Serial No. 010) to perform high-precision Sr and Nd isotope measurements, in addition to other isotope systems such as Ca and W isotopes for instance. The instrument is equipped with 16 fixed Faraday detectors, that can be dynamically connected to amplifiers with different feedback resistors (10^{10} , 10^{11} , 10^{12} and 10^{13} Ω). The fixed Faraday detectors system is compensated by the presence of a zoom-lens system located between the magnet and the detector array (Fig. 1a). This zoom-lens system is made of two lenses: quad 1 primarily focuses the individual beams, while quad 2 controls the dispersion of the beams relative to each other. The large number of detectors, in conjunction with an efficient zoom lens system, allows significant flexibility regarding the number of lines in a multidynamic acquisition routine whilst maintaining optimal peak alignment and peak shape for every measurement line despite the fact that the detectors are not movable. In practice, the natural dispersion of the Nu TIMS is such that the Re isotopes will align in adjacent collectors without the need for any quadratic field being applied to the zoom lens system. As we go lower in mass (as for Nd and Sr isotopes compared to Re), the distance between the isotopes increases (Fig. 1a-1), because lighter elements will be separated more as they pass through the magnetic sector. Applying the correct set of voltages to the zoom lens system (quad 1 and quad 2 values in Table 1, referring to the electrostatic field applied across each lens stack) will create a continuous electrostatic field which then effectively acts to demagnify the mass separation at the detectors by deflecting the isotopes increasingly when moving farther away from the central point of the lens stack (Fig. 1a-2 and 1a-3). This allows for the alignment of the isotopes into the adjacent collectors whilst maintaining good peak shapes (Fig. 1b). Optimal alignment is now achieved electrostatically and not mechanically, allowing a robust and reproducible alignment within milliseconds and insuring robust conditions for multidynamic measurements. The benefit of a multidynamic acquisition routine is a better correction for cup efficiencies compared to static measurements, a better constraint on the oxide corrections when running in negative mode (for W isotopes for instance) and a better external reproducibility. Note that for Sr and Nd isotope analyses, all the Faraday cups used were connected to amplifiers with a 10^{11} Ω feedback resistor, and a 30 min gain calibration was performed every morning.

174 Strontium isotopic measurements were performed using roughly 300 ng of Sr loaded on
 175 previously outgassed zone-refined Re single filaments. About 0.7 μl of TaF₅ activator and 1 μl
 176 of sample in 0.5N HNO₃ were loaded onto the filament, in between two Parafilm strips
 177 separated by ~ 3 mm, at ~ 0.75 A. The role of the Parafilm strips was to prevent the sample and
 178 the activator spreading on the filament during the loading, so that a small spot could be obtained.
 179 The activator and the sample were left to dry down between each step. The Parafilm strips were
 180 then burnt off at ~ 1.6 A and the filament glowed briefly to dull red at ~ 2.0 A. Rubidium
 181 interferences were monitored on the TIMS using ⁸⁵Rb, but even in the case of residual rubidium,
 182 it was burnt off from the filament before the strontium was properly emitted. The sample
 183 filament was slowly heated until a stable ⁸⁸Sr⁺ beam of ~ 12 -13 V was obtained and typically
 184 measured for 6-7 h (corresponding to ~ 200 cycles, with a total acquisition time of 80 s per
 185 cycle). The run length was variable and depended on when the sample was consumed. This
 186 translated into ‘raw’ ⁸⁶Sr/⁸⁸Sr typically close to 0.1204 at the start of an analysis and lower than
 187 0.1185 (and sometimes even down to 0.1180) when the analysis stopped. Baselines were
 188 measured for 3 min every 20 cycles and peaks were recentred every 40 cycles.

189 Strontium isotopes were measured using a 5 lines acquisition routine (Table 1a). The
 190 ⁸⁷Sr/⁸⁶Sr and ⁸⁴Sr/⁸⁶Sr acquired in each line were corrected for instrumental mass fractionation
 191 with the exponential law using the ⁸⁶Sr/⁸⁸Sr acquired in the same line and assuming (⁸⁶Sr/⁸⁸Sr)_{ref}
 192 = 0.1194. A multi-static ⁸⁷Sr/⁸⁶Sr (hereafter (⁸⁷Sr/⁸⁶Sr)_{multistat}) and a multi-static ⁸⁴Sr/⁸⁶Sr
 193 (hereafter (⁸⁴Sr/⁸⁶Sr)_{multistat}) can then be obtained by averaging the 5 static ⁸⁷Sr/⁸⁶Sr acquired in
 194 the 5 lines and the 4 static ⁸⁴Sr/⁸⁶Sr acquired in the first 4 lines, respectively. A dynamic ⁸⁷Sr/⁸⁶Sr
 195 is obtained by combining the measurements from two different magnetic field positions (e.g.,
 196 lines 1 -2, Table 1a), following:

$$197 \quad \left(\frac{{}^{87}\text{Sr}}{{}^{86}\text{Sr}}\right)_{1-2} = \sqrt{\left(\frac{{}^{87}\text{Sr}_{H9}}{{}^{86}\text{Sr}_{H7}}\right)_1 \times \left(\frac{{}^{87}\text{Sr}_{H7}}{{}^{86}\text{Sr}_{H9}}\right)_2 \times \left(\frac{{}^{88}\text{Sr}}{{}^{86}\text{Sr}}\right)_{ref}} \quad (1)$$

198 We can note that a correction for time-drift is applied for dynamic ratios (Garçon et al. 2018),
 199 and although the drift correction code may not be identical to Garçon et al. (2018), a similar
 200 effect can be seen. This time drift correction is utilized to minimize effects associated with a
 201 growing or changing signal emission between magnet positions. It does so by adding an extra
 202 measurement line at the start of each block and comparing this measurement to the following
 203 for a correction back to a set time and intensity. A multi-dynamic ⁸⁷Sr/⁸⁶Sr (hereafter
 204 (⁸⁷Sr/⁸⁶Sr)_{multidyn}) can then be obtained by averaging the 4 dynamic ⁸⁷Sr/⁸⁶Sr. As mentioned
 205 earlier, we favoured dynamic measurements because they allow for the effective correction of
 206 potential differences in cup efficiencies and amplifier gains between Faraday detectors. Using
 207 the analytical conditions described above (very long and high intensity analysis), we obtained
 208 internal precision for an individual Sr analysis typically better than 2×10^{-6} (2 se) on
 209 (⁸⁷Sr/⁸⁶Sr)_{multidyn} (Fig.2). In comparison, a 2 hours analysis (corresponding to more
 210 ‘conventional’ Sr isotope studies but with much higher intensities) gives an internal precision
 211 typically around 2.5×10^{-6} (2 se) on (⁸⁷Sr/⁸⁶Sr)_{multidyn} (Fig.2). Finally, assuming that our analyses
 212 are made with a ⁸⁸Sr signal 4 to 10 times higher than ‘conventional’ Sr isotopes studies, we can
 213 estimate the internal precisions that would be obtained for 2 hours runs at low signal (1-3V on
 214 ⁸⁸Sr); these would be ~ 5 -8 $\times 10^{-6}$ (Fig. 2). Such values are comparable to the internal precisions

215 obtained in similar conditions and using other TIMS (e.g., Carpentier et al. 2014) or another Nu
 216 TIMS (e.g., Fourny et al. 2016, 2019).

217

218 Neodymium isotopic measurements were performed using between 600 ng and 800 ng
 219 of Nd loaded on previously outgassed zone-refined Re double filaments. About 1 μ l of sample
 220 in 0.5N HNO₃ was loaded onto the sample filament, in between two Parafilm strips at \sim 0.75
 221 A. Once dried, roughly 0.5 μ l of 1N H₃PO₄ activator was loaded on top of the sample at \sim 1.2
 222 A. Then, once the activator was dried and similarly to Sr, the Parafilm strips were burnt off at
 223 \sim 1.6 A and the filament glowed briefly to dull red at \sim 2.0 A. After having heated the ioniser
 224 filament to a temperature of \sim 1900°C in the source chamber, the sample filament was slowly
 225 heated until a stable ¹⁴²Nd⁺ beam of \sim 6-8 V was obtained and typically measured for 7-8 h
 226 (corresponding to \sim 300 cycles, with a total acquisition time of 50 s per cycle). Unlike for Sr
 227 analyses, we did not systematically run until the Nd was totally consumed. However, if the
 228 sample was getting exhausted by the end of an analysis, it translated into ‘raw’ ¹⁴⁶Nd/¹⁴⁴Nd
 229 typically starting at 0.7200 to finish at 0.7250 when the analysis was stopped. Baselines were
 230 measured for 3 min every 20 cycles, and peaks were recentred every 60 cycles.

231 Similarly to the Sr method, Nd isotopes were measured using a 5 lines acquisition
 232 routine (Table 1b). The method and the equations described in this paper for Nd isotope
 233 measurements on the Nu TIMS are adapted from Thirlwall (1991) and Garçon et al. (2018).
 234 The ¹⁴³Nd/¹⁴⁴Nd, ¹⁴⁵Nd/¹⁴⁴Nd, ¹⁴⁸Nd/¹⁴⁴Nd and ¹⁵⁰Nd/¹⁴⁴Nd acquired in each line were corrected
 235 for instrumental mass fractionation with the exponential law using the ¹⁴⁶Nd/¹⁴⁴Nd acquired in
 236 the same line and assuming (¹⁴⁶Nd/¹⁴⁴Nd)_{ref} = 0.7219. A multi-static ⁱNd/¹⁴⁴Nd (hereafter
 237 (ⁱNd/¹⁴⁴Nd)_{multistat}, with i = 143, 145, 148 or 150) can then be obtained by averaging the 5 static
 238 ⁱNd/¹⁴⁴Nd acquired in the 5 lines. Dynamic ¹⁴³Nd/¹⁴⁴Nd and ¹⁴⁵Nd/¹⁴⁴Nd are obtained by
 239 combining the measurements from three different magnetic field positions (i.e. lines 1-2-3, 2-
 240 3-4 or 3-4-5, Table 1b), following for instance:

$$241 \quad \left(\frac{{}^{143}\text{Nd}}{{}^{144}\text{Nd}}\right)_{1-2-3} = \sqrt{\left(\frac{{}^{143}\text{Nd}_{H1}}{{}^{144}\text{Nd}_{H2}}\right)_3 \times \left(\frac{{}^{143}\text{Nd}_{Ax}}{{}^{144}\text{Nd}_{H1}}\right)_2 \times \left(\frac{m_{143}}{m_{144}}\right)^{2F_1}} \quad (2)$$

$$242 \quad \text{With } F_1 = \frac{\ln\left(\frac{\left(\frac{{}^{146}\text{Nd}}{{}^{144}\text{Nd}}\right)_{ref}}{\left(\frac{{}^{146}\text{Nd}_{H2}}{{}^{144}\text{Nd}_{Ax}}\right)_1}\right)}{\ln\left(\frac{m_{146}}{m_{144}}\right)} \quad (3)$$

243 Dynamic ¹⁴⁸Nd/¹⁴⁴Nd and ¹⁵⁰Nd/¹⁴⁴Nd are obtained by combining the measurements from two
 244 different magnetic field positions (i.e. lines 1-3, 2-4 or 3-5, Table 1b), following for instance:

$$245 \quad \left(\frac{{}^{148}\text{Nd}}{{}^{144}\text{Nd}}\right)_{1-3} = \left(\frac{{}^{148}\text{Nd}_{H4}}{{}^{146}\text{Nd}_{H2}}\right)_1 \times \left(\frac{{}^{146}\text{Nd}}{{}^{144}\text{Nd}}\right)_{ref} \times \left(\frac{m_{148}}{m_{146}}\right)^{F_3} \quad (4)$$

$$246 \quad \text{With } F_3 = \frac{\ln\left(\frac{\left(\frac{{}^{146}\text{Nd}}{{}^{144}\text{Nd}}\right)_{ref}}{\left(\frac{{}^{146}\text{Nd}_{H4}}{{}^{144}\text{Nd}_{H2}}\right)_3}\right)}{\ln\left(\frac{m_{146}}{m_{144}}\right)} \quad (5)$$

247 As in the Sr procedure, a correction for time-drift is applied for dynamic ratios. A multi-
248 dynamic ${}^i\text{Nd}/{}^{144}\text{Nd}$ (hereafter $({}^i\text{Nd}/{}^{144}\text{Nd})_{\text{multidyn}}$) can then be obtained by averaging the 3
249 dynamic ${}^i\text{Nd}/{}^{144}\text{Nd}$. Using the analytical conditions described above (very long and high
250 intensity analysis), we obtain internal precision for an individual Nd analysis typically better
251 than 1×10^{-6} (2 se) on $({}^{143}\text{Nd}/{}^{144}\text{Nd})_{\text{multidyn}}$. We do not report values for ${}^{142}\text{Nd}/{}^{144}\text{Nd}$ in this paper
252 because the chromatographic procedure used in the course of this study was not designed to
253 remove Pr and Ce from Nd (Table 2b).

254

255 *b. Reproducibility of pure standard solutions*

256

257 We obtain $({}^{87}\text{Sr}/{}^{86}\text{Sr})_{\text{multidyn}} = 0.7102467 \pm 0.0000043$ (6.0 ppm, 2 s.d., $n = 38$) for NBS
258 987 (Fig. 3) and $({}^{143}\text{Nd}/{}^{144}\text{Nd})_{\text{multidyn}} = 0.5119537 \pm 0.0000022$ (4.2 ppm, 2 s.d., $n = 31$) for
259 Rennes-Ames (Fig. 4). We can note here that if we consider only the sub data corresponding to
260 the first 60 cycles (~ 2 hours) of each NBS 987 analysis, we obtain similar values, i.e.
261 $({}^{87}\text{Sr}/{}^{86}\text{Sr})_{\text{multidyn}} = 0.7102456 \pm 0.0000044$ (6.2 ppm, 2 s.d., $n = 38$). These data are consistent
262 with the data reported in the literature, however the external precisions reported here on pure
263 standard solutions are two to three times better than the most precise published data for
264 ${}^{87}\text{Sr}/{}^{86}\text{Sr}$, and comparable to the most precise literature data for ${}^{143}\text{Nd}/{}^{144}\text{Nd}$ (Table 3 and Fig.
265 3a and 4a).

266 Our measurement of JNdi-1 gives $({}^{143}\text{Nd}/{}^{144}\text{Nd})_{\text{multidyn}} = 0.5120941 \pm 0.0000022$ (4.4 ppm,
267 2 s.d., $n = 9$), which is slightly lower than the reference value of 0.512115 ± 0.000007 reported
268 in Tanaka et al. (2000). However, our $({}^{143}\text{Nd}/{}^{144}\text{Nd})_{\text{multidyn}}$ is in agreement with the high-
269 precision data of 0.512099 ± 0.000005 (9.2 ppm, 2 s.d., $n = 54$) reported in Garçon et al. (2018).
270 It is also very close to the latest high-precision data reported by Pin and Gannoun (2019 a,b) of
271 0.512101 ± 0.000003 (5.9 ppm, 2 s.d., $n = 12$) and 0.512104 ± 0.000003 (5.9 ppm, 2 s.d., $n =$
272 15). We note that despite plotting within error of each other, the two values reported by Pin and
273 Gannoun indicate that small variations can occur for analyses run on the same instrument in the
274 same laboratory, even in the course of high precision isotope work.

275 Also, as seen in Figure 3b, there is no resolvable difference between $({}^{87}\text{Sr}/{}^{86}\text{Sr})_{\text{multidyn}}$ and
276 $({}^{87}\text{Sr}/{}^{86}\text{Sr})_{\text{multistat}}$, which is expected when the drift in the mass bias is corrected properly and the
277 Faraday cups show little evidence for deterioration (the detectors have been used for less than
278 a year in the course of this study). Similarly to ${}^{87}\text{Sr}/{}^{86}\text{Sr}$, there seems to be no significant offset
279 between $({}^{143}\text{Nd}/{}^{144}\text{Nd})_{\text{multidyn}}$ and $({}^{143}\text{Nd}/{}^{144}\text{Nd})_{\text{multistat}}$, the difference between the two ratios
280 being on average ~ 2 ppm, i.e. within error (Fig. 4b). It is also important to note that for the Nd
281 systematics, the multidynamic method yields more reproducible data than the multistatic
282 method, translating into a smaller error on the mean ratio (± 0.0000022 versus ± 0.0000040 on
283 the ${}^{143}\text{Nd}/{}^{144}\text{Nd}$, 2 s.d., $n = 31$). For the Sr systematics, both methods seem to give comparable
284 reproducibility at the moment (± 0.0000043 versus ± 0.0000041 on the ${}^{87}\text{Sr}/{}^{86}\text{Sr}$, 2 s.d., $n=38$).
285 One thing worth to note here is that, as shown in Figure 4b, the ${}^{143}\text{Nd}/{}^{144}\text{Nd}$ seems to decrease
286 with time (for both $({}^{143}\text{Nd}/{}^{144}\text{Nd})_{\text{multidyn}}$ and $({}^{143}\text{Nd}/{}^{144}\text{Nd})_{\text{multistat}}$). The origin of this drift is not
287 clear to us yet, but we believe it could be several things, from how the beam behaves (growing
288 or dying), how it fractionates (i.e. reverse fractionation occurring; e.g., Garçon et al. 2018) to
289 the gain or the bucket efficiency. Thus, if we can see a 4 ppm change between running the

290 analysis using a standard or reverse cup configuration (see below), maybe the same could be
291 seen between a growing and dying signal. Alternatively, a good indication of bucket efficiency
292 would be to monitor how the $^{143}\text{Nd}/^{144}\text{Nd}$ static ratios behave individually when the gain is
293 stable over a time period. However, we could not see one $(^{143}\text{Nd}/^{144}\text{Nd})_{\text{stat}}$ being systematically
294 and significantly lower than the others. Overall, it is difficult to say what causes this change
295 given it is a very small change.

296 Furthermore, we have compared two reverse methods (Table 1b and 1c) for Nd isotope
297 measurements on the pure standard solution Rennes-Ames and have noticed the
298 $(^{143}\text{Nd}/^{144}\text{Nd})_{\text{multidyn}}$ obtained with each method were within errors of each other. Thus, in
299 February 2021, we obtained a $(^{143}\text{Nd}/^{144}\text{Nd})_{\text{multidyn}}$ of 0.5119535 ± 0.0000013 (2.5 ppm, 2 s.d.,
300 $n = 7$) with the cup configuration reported in table 1b, which is within error of
301 $(^{143}\text{Nd}/^{144}\text{Nd})_{\text{multidyn}} = 0.5119514 \pm 0.0000018$ (3.5 ppm, 2 s.d., $n = 5$) obtained with the reverse
302 method reported in table 1c. The relative difference between those two values is of ~ 4 ppm.
303 Similarly, we obtained the same relative difference of ~ 4 ppm for $(^{143}\text{Nd}/^{144}\text{Nd})_{\text{multidyn}}$ between
304 the two Nd reverse methods in June 2021, with the cup configuration reported in table 1b giving
305 0.5119500 ± 0.0000004 and the set-up reported in Table 1c giving 0.5119481 ± 0.0000007 .
306 Overall, although the method reported in Table 1b seems to give a slightly higher
307 $(^{143}\text{Nd}/^{144}\text{Nd})_{\text{multidyn}}$, this is not significant compared to the external reproducibility (2 s.d.) of
308 4-5 ppm reported in this study for $(^{143}\text{Nd}/^{144}\text{Nd})_{\text{multidyn}}$. The cup configuration reported in Table
309 1b was the one finally used during this study.

310 Finally, the data obtained in this study for stable isotopes, i.e. $^{84}\text{Sr}/^{86}\text{Sr} = 0.0564902 \pm$
311 0.0000018 (31.9 ppm, 2 s.d., $n = 38$) for NBS 987, and $^{145}\text{Nd}/^{144}\text{Nd} = 0.3484004 \pm 0.0000013$
312 (3.7 ppm, 2 s.d., $n = 31$), $^{148}\text{Nd}/^{144}\text{Nd} = 0.2415798 \pm 0.0000019$ (8.0 ppm, 2 s.d., $n = 31$) and
313 $^{150}\text{Nd}/^{144}\text{Nd} = 0.2364508 \pm 0.0000056$ (23.5 ppm, 2 s.d., $n = 31$) for Rennes-Ames, are
314 consistent with previous studies (Table 3). The precisions reported here on those ratios are
315 comparable to the latest high-precision isotope data reported in Burkhardt et al. (2019) for the
316 Sr standard solution NBS 987 and Pin and Gannoun (2019) for the Nd standard solution
317 Rennes-Ames (Fig. 5).

318

319 *c. Precision*

320

321 In this section, we compare the actual errors of our analyses on the Nu TIMS with the
322 theoretical uncertainties expected from Johnson-Nyquist noise and counting statistics, these
323 processes being considered as the two main contributors to the observed internal uncertainty
324 for a given analysis. The reader is referred to the supplementary section of Luu et al. (2019) for
325 more details about the theoretical uncertainty model and the calculations, but the important
326 details are summarized below.

327 Johnson-Nyquist noise (σ_{Johnson}), the phenomenon of thermally-generated voltage noise
328 in the feedback resistor, has a standard deviation given by $\sigma_{\text{Johnson}} = \sqrt{\frac{4RkT}{t}}$, where R is the
329 feedback resistor of the amplifier connected to the Faraday cup (here $10^{11} \Omega$ for all cups
330 measuring Sr and Nd isotopes), k is the Boltzmann constant ($= 1.38 \times 10^{-23} \text{ J/K}$), T is the

331 amplifier housing temperature (= 307 K) and t is the total integration time (= integration time
332 per static measurement \times total number of cycles). Note that we include this noise in our
333 uncertainty model for completeness, but it is insignificant compared to the shot noise. Counting
334 statistics ($\sigma_{counting}$), or shot noise, describes the statistics of the arrival of ions at the detector as
335 a Poisson distribution. It is given by $\sigma_{counting} = \sqrt{\frac{V_m R e}{t}}$, where V_m is the mean amplifier output
336 voltage over the total integration time t , and e is the elementary charge (= 1.60×10^{-19} C).
337 Combining these errors by adding in quadrature the total absolute error on each isotope gives
338 $\sigma_{abs}^x = \sqrt{\sigma_{Johnson}^2 + \sigma_{counting}^2}$, and the total relative error can be written as $\sigma_{rel}^x = \frac{\sigma_{abs}^x}{V_m^x}$, with
339 $x = 86, 87$ or 88 for Sr isotopes for instance. From there, the 2 s.e. relative error on the
340 $(^{87}\text{Sr}/^{86}\text{Sr})_{multidyn}$ is derived by the quintuple jump type error propagation calculation as:
341 $2se_{rel}^{multidyn} = 2 \times \frac{1}{2n} \sqrt{n \times (\sigma_{rel}^x)^2 + n \times (\sigma_{rel}^z)^2 + (4n - 2) \times (\sigma_{rel}^y)^2}$, where n correspond
342 to the number of static measurements $- 1$ (so $n = 4$ in our case). Finally, the 2 s.e. absolute error
343 on the $(^{87}\text{Sr}/^{86}\text{Sr})_{multidyn}$ is calculated as: $2se_{abs}^{multidyn} = 2se_{rel}^{multidyn} \times \frac{A_{87}}{A_{86}}$, where A_{87} and A_{86}
344 correspond to the relative abundances of ^{87}Sr (7.00%) and ^{86}Sr (9.86%) isotopes, respectively.
345 The reader is referred to the supplementary information of this paper for more details about
346 these equations and the error propagation calculations.

347 The results of that model are plotted in Figure 6, for the case of Sr systematics. We chose
348 to plot the typical internal precisions (2 s.e.) for $(^{87}\text{Sr}/^{86}\text{Sr})_{multidyn}$ against $1/\sqrt{\text{number of ions}}$
349 detected) because this latter parameter reflects the total integration time, while accounting for
350 the different average total intensities of the dataset. On figure 6a, we can clearly see that the
351 data fall below the model, for both the geostandards and the pure standard solution NBS 987.
352 This is unexpected and may not look correct at first glance. However, we used a Monte Carlo
353 simulation for the quintuple-jump uncertainty on the ratio and it agrees well with the error
354 propagation model described above, so we are confident that the discrepancy between the actual
355 and the theoretical errors is not due to a mistake in the algebra of propagating the errors.
356 We then investigated the effect of the time-drift correction. As mentioned earlier, a correction
357 for time-drift is applied for dynamic ratios. This is because the use of a time-drift correction in
358 a dynamic routine helps reducing possible fractionation changes between measurement lines,
359 which could cause a bias on the final ratio as suggested in Garçon et al. (2018) and observed
360 by Roth et al. (2014). We note that although the drift correction code may not be identical to
361 Garçon et al. (2018), a similar effect can be seen. If the time-drift correction is ignored, it
362 appears that the data are now consistent with the model (Fig. 6b): the typical uncertainties
363 reported in Table 3 for both pure standard solution NBS987 and terrestrial rock standards are
364 now very close to the modelled errors, showing that (i) there is no effect of the matrix on the
365 precision of an analysis, and that (ii) the Nu TIMS is performing at the best of its capabilities.
366 We can note that the $(^{87}\text{Sr}/^{86}\text{Sr})_{multidyn}$ with and without time drift correction are differing by
367 less than 4 ppm (Table 4), which is not significant compared to the 6 ppm external
368 reproducibility we report. Thus, all the data reported in this paper have been processed using a
369 time drift correction.

370
371

372 4. Results for terrestrial rock standards

373

374 The $(^{87}\text{Sr}/^{86}\text{Sr})_{\text{multidyn}}$ and $(^{143}\text{Nd}/^{144}\text{Nd})_{\text{multidyn}}$ obtained for rock standards in this study are
375 reported in Table 3. All the results obtained by our method are in agreement with published
376 data (Fig. 7 and 8). For instance, we obtained $(^{87}\text{Sr}/^{86}\text{Sr})_{\text{multidyn}} = 0.7034750 \pm 0.0000023$ (3.3
377 ppm, 2 s.d., $n = 4$) and $(^{143}\text{Nd}/^{144}\text{Nd})_{\text{multidyn}} = 0.5129662 \pm 0.0000025$ (4.8 ppm, 2 s.d., $n = 4$)
378 for BHVO-2, and $(^{87}\text{Sr}/^{86}\text{Sr})_{\text{multidyn}} = 0.7039814 \pm 0.0000059$ (8.3 ppm, 2 s.d., $n = 4$) and
379 $(^{143}\text{Nd}/^{144}\text{Nd})_{\text{multidyn}} = 0.5127702 \pm 0.0000033$ (6.4 ppm, 2 s.d., $n = 3$) for AGV-2. We should
380 note that the variability in $^{143}\text{Nd}/^{144}\text{Nd}$ for JNdi-1 between different studies (see section 3.b)
381 has to be taken into account when comparing the $^{143}\text{Nd}/^{144}\text{Nd}$ in the literature for terrestrial
382 standards. The important thing to note here is that, for both systems, the precisions reported in
383 this study are much better than most previous studies (Fig. 7 and 8), with an external
384 reproducibility of typically 5-6 ppm (2 s.d.) for $^{87}\text{Sr}/^{86}\text{Sr}$ and 4-5 ppm (2 s.d.) for $^{143}\text{Nd}/^{144}\text{Nd}$.
385 We can also note that, although our chemistry protocol does not remove ^{141}Pr nor ^{140}Ce (with
386 typically $2 < ^{141}\text{Pr}^+ / ^{146}\text{Nd}^+ < 4$ and $^{140}\text{Ce}^+ / ^{146}\text{Nd}^+ < 1$ for rock standards at the start of an
387 analysis), this does not seem to affect the accuracy of the $^{143}\text{Nd}/^{144}\text{Nd}$.

388

389

390 5. Implications

391

392 The level of precision reached for Sr and Nd systematics in this study opens new
393 perspectives in the field of Earth Sciences, but not only.

394 Indeed, the extent of the application of radiogenic isotopes is not restricted to Earth
395 Sciences. In archaeology, $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ represent a powerful tool as source tracers.
396 For instance, small differences in isotope ratios can be decisive in discriminating sources at the
397 origin of raw materials that have been used for making prehistoric artefacts, and this
398 information can be precious to understand patterns of migrations and/or interactions between
399 prehistoric societies. However, few data have been produced with good precision (e.g., Weisler
400 et al. 2016, Hermann et al. 2017) and thereby most studies have limited conclusions given the
401 geochemical similarity of sources and some unclear geological complications regarding the
402 source of Sr (e.g., Thomsen and Andreasen, 2019).

403 In cosmochemistry, small isotopic anomalies, commonly down to the ppm level, are
404 present among solar system materials at a planetary scale, and so, being able to detect them
405 provide important constraints on planetary bodies relationships and the dynamical evolution of
406 the solar system. Considering Sr isotopes, the level of analytical precision of most studies (~ 8 -
407 10 ppm, 2 s.e.; e.g., Hans et al. 2013, Henshall et al. 2018) did not allow identification of mass-
408 independent variations in $^{84}\text{Sr}/^{86}\text{Sr}$ between enstatite chondrites, ordinary chondrites, eucrites,
409 Moon, Mars and the Earth; only carbonaceous chondrites showed small resolvable positive
410 anomalies in ^{84}Sr , between 40 and 60 ppm relative to NBS 987 (e.g., Moynier et al. 2012). The
411 latest study of bulk planetary materials by Burkhardt et al. (2019) has modified this picture,
412 reporting ordinary and enstatite chondrites, as well as Moon, with small resolvable negative

413 anomalies in ^{84}Sr , on the order of -10 to -20 ppm relative to NBS 987. This demonstrates that
414 improving analytical precision is key to better resolve small isotopic variability, and thus why
415 the level of precision reached for $^{84}\text{Sr}/^{86}\text{Sr}$ in this study (2 s.e. of ~ 5 ppm, Fig. 5a) is useful.
416 The same reasoning could be true for other systematics, e.g. mass-independent variations in
417 ^{40}Ca .

418 High precision data such as those reported in this study also opens new chronology
419 perspectives. Even if most of the uncertainty on ages comes from the poor determination of the
420 parent/daughter ratio, enhanced precision on the isotopic ratio translates into a smaller
421 propagated uncertainty on the age determined from Rb-Sr or Sm-Nd isochrons (Fig. 9). We
422 should be able to obtain Rb-Sr or Sm-Nd isochrons for much younger rocks, with greater
423 resolution between previously indistinguishable suites. We should also be able to obtain
424 isochrons for phases with lower Rb/Sr or Sm/Nd, for which the excesses in the decay products
425 of ^{87}Rb and ^{143}Sm will be small but now detectable with our improved analytical precisions on
426 $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$. For example, recently, Baxter et al. (2017) reported high-precision
427 Sm-Nd dating of individual growth zones within single garnet crystals in eclogites and other
428 metamorphic rocks, and highlighted multistage processes occurring in subduction.

429 In mantle geochemistry, small scale mantle heterogeneities, such as those discovered when
430 Pb isotopes started being measured with high precision (e.g., Abouchami et al. 2005), might be
431 discovered for volcanic rocks in both Sr and Nd isotopic spaces. Indeed, before the study by
432 Abouchami et al. (2005), the two chains of Hawaiian volcanoes Loa and Kea were thought to
433 have overlapping radiogenic isotope features (for Pb, Sr and Nd systematics). However, the
434 high precision Pb isotope data reported for the first time in Abouchami et al. (2005) thanks to
435 a Pb triple-spike technique have allowed to differentiate the Loa and Kea trends, with only a
436 very little compositional overlap. Similar discoveries could be expected with the improvement
437 in precision of Sr and Nd isotope data as reported in our study.

438 Finally, the preservation in the Earth's deep interior of early-formed material, either
439 recycled from the surface reservoirs or residual from the early mantle differentiation, has
440 recently been evidenced by the detection of small variability in ^{182}W (Mundl et al. 2017, Rizo
441 et al. 2016) and ^{142}Nd (Peters et al. 2018), the decay products of the short-lived ^{182}Hf (half-life
442 of 8.9 Myr) and ^{146}Sm (half-life of 103 Myr), respectively. The total range of variations among
443 modern ocean island basalts does not exceed 15 ppm in $^{142}\text{Nd}/^{144}\text{Nd}$ and 25 ppm for $^{182}\text{W}/^{184}\text{W}$.
444 These small variabilities have become detectable thanks to the high analytical precisions
445 recently reached with dynamic measurements on the TIMS, i.e. ± 4 ppm on $^{182}\text{W}/^{184}\text{W}$ (2 s.d.;
446 Mundl et al. 2017) and ± 4.4 ppm on $^{142}\text{Nd}/^{144}\text{Nd}$ (2 s.d., in Peters et al. 2018). These recent
447 discoveries are very exciting and we are currently developing analytical methods for high
448 precision ^{182}W and ^{142}Nd isotope measurements on our Nu TIMS at IPGP, in order to expand
449 the currently limited dataset available.

450

451

452 **6. Conclusions**

453

454 We report high-precision Sr and Nd isotope data, with an external reproducibility on the
455 order of 5-6 ppm (2 s.d.) for $^{87}\text{Sr}/^{86}\text{Sr}$ and 4-5 ppm (2 s.d.) for $^{143}\text{Nd}/^{144}\text{Nd}$. This is the first time

456 such a level of precision is reported with a TIMS from Nu Instruments. Such precisions are of
457 key importance in the field of Earth Sciences because Sr and Nd systematics are powerful tools
458 to trace sources of materials and to date them, but they also open new opportunities in fields
459 such as cosmochemistry, paleoclimatic studies, archaeology, tracing of food origin or forensics.

460
461

462 7. Acknowledgements

463

464 This work was supported by grant from European Research Council (ERC grant SHRED,
465 Grant Agreement no. [833632] – Survival of Hadean REmnants in a Dynamic mantle). THL
466 would like to thank Christopher Coath from the Bristol Isotope Group for his expertise
467 regarding the statistics and error propagation section and acknowledge authorship of the
468 derivation of the theoretical uncertainty provided in the supplementary information. We thank
469 Tod Waight and an anonymous reviewer for their constructive reviews that allowed for a much-
470 improved manuscript. We also thank Balz Kamber for editorial handling.

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473 8. References

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635 TABLE 1: Collector configuration used for Sr (a) and Nd (b) isotope measurements on the Nu TIMS during the course of this study. Note that the
 636 numbers in bold purple correspond to the mass used for the peak centering for each line. (c) Reverse configuration for Nd used to test if there is
 637 any difference between methods b and c.

638

639 a.

Sr configuration	H11	H9	H7	H5	H3	H1	L1	L3	Integration time (s)	Quad 1 (V)	Quad 2 (V)
Line 1	88	87	86	85	84	83	82	81	16	27	-27
Line 2	89	88	87	86	85	84	83	82	16	28	-42
Line 3	90	89	88	87	86	85	84	83	16	33	-61
Line 4	91	90	89	88	87	86	85	84	16	34	-77
Line 5	92	91	90	89	88	87	86	85	16	36	-91

640

641 b.

Nd configuration	H11	H10	H9	H8	H7	H6	H5	H4	H3	H2	H1	Ax	L1	L2	L3	L4	Integration time (s)	Quad 1 (V)	Quad 2 (V)
Line 1	155	154	153	152	151	150	149	148	147	146	145	144	143	142	141	137	10	-15	127
Line 2	154	153	152	151	150	149	148	147	146	145	144	143	142	141	140	136	10	-15	134
Line 3	153	152	151	150	149	148	147	146	145	144	143	142	141	140	139	135	10	-17	139
Line 4	152	151	150	149	148	147	146	145	144	143	142	141	140	139	138	134	10	-17	145
Line 5	151	150	149	148	147	146	145	144	143	142	141	140	139	138	137	133	10	-17	148

642

643 c.

Nd Reverse	H11	H10	H9	H8	H7	H6	H5	H4	H3	H2	H1	Ax	L1	L2	L3	L4	Integration time (s)	Quad 1 (V)	Quad 2 (V)
Line 1	151	150	149	148	147	146	145	144	143	142	141	140	139	138	137	133	10	-18	149
Line 2	152	151	150	149	148	147	146	145	144	143	142	141	140	139	138	134	10	-18	146
Line 3	153	152	151	150	149	148	147	146	145	144	143	142	141	140	139	135	10	-18	140
Line 4	154	153	152	151	150	149	148	147	146	145	144	143	142	141	140	136	10	-17	137
Line 5	155	154	153	152	151	150	149	148	147	146	145	144	143	142	141	137	10	-17	131

644

645 TABLE 2: a. Potential interferences (a) in the mass region 84-88 affecting the Sr isotope results
 646 and (b) in the mass region 142-150 affecting the Nd isotope results. In practice, Kr, oxides and
 647 doubly charged ions constitute a major issue when using plasma source mass spectrometers,
 648 but they are very rare when using a TIMS. Only interferences coming from Rb and Ce-Sm (bold
 649 purple) are considered when measuring Sr and Nd isotopes on a TIMS. A good Sr and Nd
 650 chemical separation prior to isotope analyses on the TIMS is mandatory.

651
 652

a.

Sr	$^{84}\text{Sr}^+$	$^{86}\text{Sr}^+$	$^{87}\text{Sr}^+$	$^{88}\text{Sr}^+$
Kr	$^{84}\text{Kr}^+$	$^{86}\text{Kr}^+$		
Rb			$^{87}\text{Rb}^+$	
REE	$^{168}\text{Yb}^{2+}$ $^{168}\text{Er}^{2+}$	$^{172}\text{Yb}^{2+}$	$^{174}\text{Yb}^{2+}$	$^{176}\text{Yb}^{2+}$ $^{176}\text{Lu}^{2+}$ $^{176}\text{Hf}^{2+}$
Fe oxides		$^{54}\text{Fe}^{16}\text{O}_2^+$	$^{54}\text{Fe}^{16}\text{O}^{17}\text{O}^+$	$^{54}\text{Fe}^{16}\text{O}^{18}\text{O}^+$ $^{54}\text{Fe}^{17}\text{O}_2^+$ $^{56}\text{Fe}^{16}\text{O}_2^+$
Zn oxides	$^{68}\text{Zn}^{16}\text{O}^+$	$^{68}\text{Zn}^{18}\text{O}^+$ $^{70}\text{Zn}^{16}\text{O}^+$	$^{70}\text{Zn}^{17}\text{O}^+$	$^{70}\text{Zn}^{18}\text{O}^+$
Ga oxides		$^{69}\text{Ga}^{17}\text{O}^+$	$^{69}\text{Ga}^{18}\text{O}^+$ $^{71}\text{Ga}^{16}\text{O}^+$	$^{71}\text{Ga}^{17}\text{O}^+$
Ca dimers	$^{40}\text{Ca}^{44}\text{Ca}^+$ $^{42}\text{Ca}_2^+$	$^{40}\text{Ca}^{46}\text{Ca}^+$ $^{42}\text{Ca}^{44}\text{Ca}^+$ $^{43}\text{Ca}_2^+$	$^{43}\text{Ca}^{44}\text{Ca}^+$	$^{40}\text{Ca}^{48}\text{Ca}^+$ $^{42}\text{Ca}^{46}\text{Ca}^+$ $^{44}\text{Ca}_2^+$

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b.

Nd	^{142}Nd	^{143}Nd	^{144}Nd	^{145}Nd	^{146}Nd	^{148}Nd	^{150}Nd
Ce	$^{142}\text{Ce}^+$						
Sm			$^{144}\text{Sm}^+$			$^{148}\text{Sm}^+$	$^{150}\text{Sm}^+$
Ba oxides					$^{130}\text{Ba}^{16}\text{O}$	$^{132}\text{Ba}^{16}\text{O}$	$^{134}\text{Ba}^{16}\text{O}$ $^{132}\text{Ba}^{18}\text{O}$
Ru oxides			$^{96}\text{Ru}^{16}\text{O}_3^+$		$^{98}\text{Ru}^{16}\text{O}_3^+$	$^{100}\text{Ru}^{16}\text{O}_3^+$	$^{102}\text{Ru}^{16}\text{O}_3^+$

655
 656

657 TABLE 3: Strontium and neodymium isotope compositions for pure standard solutions and terrestrial rocks measured in the course of this study.
 658 All the ratios are multidynamic except the $^{84}\text{Sr}/^{86}\text{Sr}$ which are multistatic. Rep = the solution was loaded a second time on a different filament.

		$^{87}\text{Sr}/^{86}\text{Sr}$	2se/2sd	$^{84}\text{Sr}/^{86}\text{Sr}$	2se/2sd	Yield (%)	$^{143}\text{Nd}/^{144}\text{Nd}$	2se/2sd	$^{145}\text{Nd}/^{144}\text{Nd}$	2se/2sd	$^{148}\text{Nd}/^{144}\text{Nd}$	2se/2sd	$^{150}\text{Nd}/^{144}\text{Nd}$	2se/2sd	Yield (%)
Pure standard Solutions	NBS 987	0.7102467	4.3×10^{-6}	0.0564902	1.8×10^{-6}										
	Rennes-Ames		(n = 38)		(n=38)		0.5119537	2.2×10^{-6}	0.3484004	1.3×10^{-6}	0.2415798	1.9×10^{-6}	0.2364508	5.6×10^{-6}	
Terrestrial rocks															
BHVO-2	BHVO-2 a						0.5129680	7.3×10^{-7}	0.3484000	2.2×10^{-7}	0.2415805	3.3×10^{-7}	0.2364501	5.3×10^{-7}	34
	BHVO-2 Pam	0.7034753	1.9×10^{-6}	0.0564891	5.1×10^{-7}	29	0.5129658	6.2×10^{-7}	0.3483998	1.8×10^{-7}	0.2415793	2.6×10^{-7}	0.2364491	4.5×10^{-7}	40
	BHVO-2 b	0.7034737	1.2×10^{-6}	0.0564890	4.5×10^{-7}	86	0.5129653	6.5×10^{-7}	0.3483992	2.1×10^{-7}	0.2415791	2.7×10^{-7}	0.2364487	4.0×10^{-7}	84
	BHVO-2 c	0.7034765	1.4×10^{-6}	0.0564899	5.3×10^{-7}	75	0.5129656	6.0×10^{-7}	0.3483997	1.7×10^{-7}	0.2415802	2.5×10^{-7}	0.2364502	3.6×10^{-7}	89
	BHVO-2 c rep	0.7034746	1.4×10^{-6}	0.0564883	4.4×10^{-7}										
	mean	0.7034750	2.3×10^{-6}	0.0564891	1.3×10^{-6}		0.5129662	2.5×10^{-6}	0.3483996	7.2×10^{-7}	0.2415798	1.4×10^{-6}	0.2364495	1.5×10^{-6}	
BCR-2	BCR-2 a	0.7050090	1.5×10^{-6}	0.0564898	5.1×10^{-7}	27	0.5126183	8.5×10^{-7}	0.3484002	2.9×10^{-7}	0.2415858	3.7×10^{-7}	0.2364560	5.8×10^{-7}	18
	BCR-2 b	0.7050103	9.9×10^{-7}	0.0564873	4.5×10^{-7}	78									
	BCR-2 c	0.7050093	1.3×10^{-6}	0.0564893	4.3×10^{-7}	93	0.5126142	5.1×10^{-7}	0.3483987	1.4×10^{-7}	0.2415789	1.9×10^{-7}	0.2364471	2.9×10^{-7}	90
	BCR-2 c rep	0.7050077	1.1×10^{-6}	0.0564889	4.3×10^{-7}										
		mean	0.7050091	2.2×10^{-6}	0.0564893	8.4×10^{-7}		0.5126162	5.7×10^{-6}	0.3483994	2.1×10^{-6}	0.2415824	9.7×10^{-6}	0.2364515	1.3×10^{-5}
BR-24	BR-24 a	0.7050381	1.2×10^{-6}	0.0564882	4.2×10^{-7}	87	0.5127711	5.5×10^{-7}	0.3483991	1.5×10^{-7}	0.2415791	2.3×10^{-7}	0.2364482	3.9×10^{-7}	92
	BR-24 b	0.7050380	1.6×10^{-6}	0.0564881	5.9×10^{-7}	87	0.5127711	5.3×10^{-7}	0.3483988	1.7×10^{-7}	0.2415796	2.3×10^{-7}	0.2364496	3.5×10^{-7}	89
	BR-24 b rep	0.7050379	1.2×10^{-6}	0.0564878	4.1×10^{-7}										
		mean	0.7050380	1.8×10^{-7}	0.0564880	4.2×10^{-7}		0.5127711	2.8×10^{-8}	0.3483989	4.7×10^{-7}	0.2415793	7.9×10^{-7}	0.2364489	2.1×10^{-6}
BIR-1	BIR-1 a	0.7031000	1.5×10^{-6}	0.0564888	4.7×10^{-7}	74	0.5130710	9.2×10^{-7}	0.3483992	2.7×10^{-7}	0.2415824	4.1×10^{-7}	0.2364516	5.5×10^{-7}	87
	BIR-1 b	0.7030985	1.6×10^{-6}	0.0564892	5.6×10^{-7}	71	0.5130734	9.5×10^{-7}	0.3483992	2.6×10^{-7}	0.2415795	3.6×10^{-7}	0.2364482	5.9×10^{-7}	86
	BIR-1 b rep	0.7030959	1.3×10^{-6}	0.0564898	4.2×10^{-7}										
		mean	0.7030981	4.1×10^{-6}	0.0564893	1.1×10^{-6}		0.5130722	3.5×10^{-6}	0.3483992	5.7×10^{-8}	0.2415810	4.0×10^{-6}	0.2364499	4.8×10^{-6}
Be-N	Be-N a	0.7038004	1.6×10^{-6}	0.0564873	6.0×10^{-7}	75	0.5128642	6.0×10^{-7}	0.3483994	1.8×10^{-7}	0.2415804	2.3×10^{-7}	0.2364517	3.9×10^{-7}	91
	Be-N a rep	0.7037995	1.1×10^{-6}	0.0564875	4.4×10^{-7}										
	Be-N b	0.7037999	1.5×10^{-6}	0.0564883	5.1×10^{-7}	89	0.5128617	6.1×10^{-7}	0.3483991	1.8×10^{-7}	0.2415815	2.3×10^{-7}	0.2364530	3.6×10^{-7}	86
		mean	0.7037999	8.6×10^{-7}	0.0564877	1.1×10^{-6}		0.5128629	3.5×10^{-6}	0.3483993	4.5×10^{-7}	0.2415809	1.6×10^{-6}	0.2364524	1.8×10^{-6}
RGM-1	RGM1-a					12									9
	RGM-1 b	0.7042043	1.4×10^{-6}	0.0564873	4.4×10^{-7}	71	0.5127778	6.9×10^{-7}	0.3483999	2.1×10^{-7}	0.2415802	2.6×10^{-7}	0.2364489	4.1×10^{-7}	91
	RGM-1 b rep	0.7041943	1.1×10^{-6}	0.0564886	4.1×10^{-7}										
	RGM-1 c					85									
	mean	0.7041993	1.4×10^{-5}	0.0564880	1.9×10^{-6}										
AGV-2	AGV-2 a	0.7039781	1.8×10^{-6}	0.0564908	6.1×10^{-7}	14	0.5127720	9.0×10^{-7}	0.3484012	3.3×10^{-7}	0.2415795	3.5×10^{-7}	0.2364480	6.7×10^{-7}	15
	AGV-2 b	0.7039843	9.5×10^{-7}	0.0564875	3.9×10^{-7}	85	0.5127688	6.2×10^{-7}	0.3483987	2.0×10^{-7}	0.2415780	2.6×10^{-7}	0.2364465	4.1×10^{-7}	79
	AGV-2 c	0.7039800	1.2×10^{-6}	0.0564896	4.5×10^{-7}	93	0.5127698	5.4×10^{-7}	0.3483988	1.5×10^{-7}	0.2415810	2.3×10^{-7}	0.2364508	3.6×10^{-7}	91
	AGV-2 c rep	0.7039835	1.3×10^{-6}	0.0564877	4.4×10^{-7}										
		mean	0.7039814	5.9×10^{-6}	0.0564889	3.2×10^{-6}		0.5127702	3.3×10^{-6}	0.3483996	2.8×10^{-6}	0.2415795	3.0×10^{-6}	0.2364485	4.4×10^{-6}

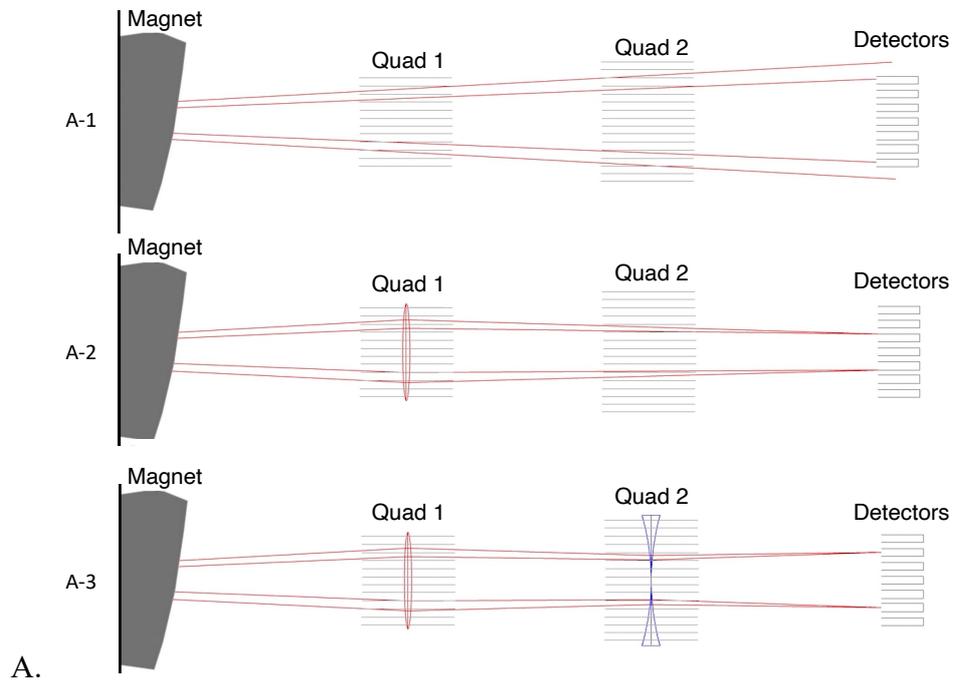
660 TABLE 4: Comparison between $(^{87}\text{Sr}/^{86}\text{Sr})_{\text{multidyn}}$ when using the time drift correction, or not.
 661

	With time drift correction		Without time drift correction		Relative difference (ppm)	n
	$^{87}\text{Sr}/^{86}\text{Sr}$	2sd	$^{87}\text{Sr}/^{86}\text{Sr}$	2sd		
NBS 987	0.7102466	4.1×10^{-6}	0.7102490	5.0×10^{-6}	3.4	37
BHVO-2	0.7034750	2.3×10^{-6}	0.7034779	2.6×10^{-6}	4.0	4
BCR-2	0.7050091	2.2×10^{-6}	0.7050112	2.8×10^{-6}	3.0	4
BR-24	0.7050380	1.8×10^{-7}	0.7050403	1.0×10^{-6}	3.2	3
BIR-1	0.7030981	4.1×10^{-6}	0.7031002	5.1×10^{-6}	3.0	3
Be-N	0.7037999	8.6×10^{-7}	0.7038028	2.0×10^{-6}	4.1	3
AGV-2	0.7039814	5.9×10^{-6}	0.7039841	5.7×10^{-6}	3.7	4

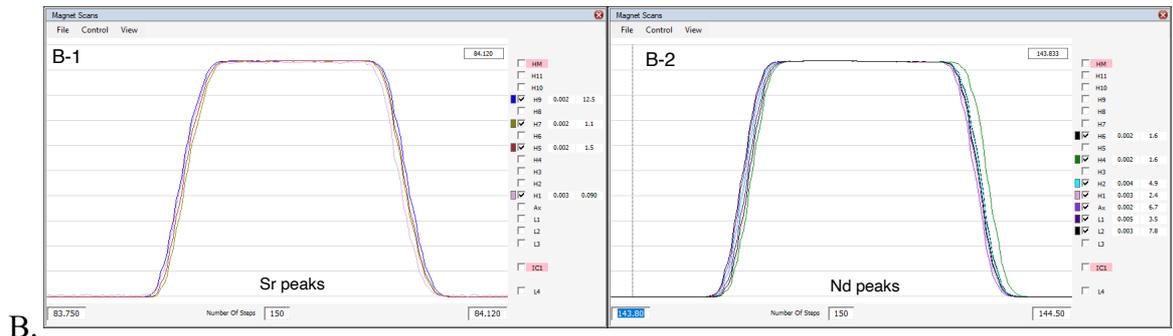
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664 **FIGURE 1:** a. Schematic showing where the zoom lens system allowing peak alignment while
 665 having fixed Faraday detectors sits on the Nu TIMS, and what happens to the ion beams when
 666 using or not the zoom lens system. a-1: No voltage is applied on quads 1 and 2, resulting in two
 667 ion beams diverging and being unfocused at the collector array. a-2: A voltage is applied on
 668 quad 1 only, resulting in two ion beams being focused but the natural dispersion of these ion
 669 beams does not align with the collector array. a-3: Voltages are now applied on both quads 1
 670 and 2, resulting in two ion beams being now focused at the correct collectors.

671 b. Peak alignment achieved with fixed Faraday detectors for Sr and Nd isotopes when applying
 672 adequate voltages on the zoom lens system. The isotopes ^{84}Sr , ^{86}Sr , ^{87}Sr and ^{88}Sr are collected
 673 in H1, H5, H7 and H9 detectors, respectively (C-1). The isotopes ^{142}Nd , ^{143}Nd , ^{144}Nd , ^{145}Nd ,
 674 ^{146}Nd , ^{148}Nd and ^{150}Nd are collected in L2, L1, Ax, H1, H2, H4 and H6, respectively (C-2).
 675

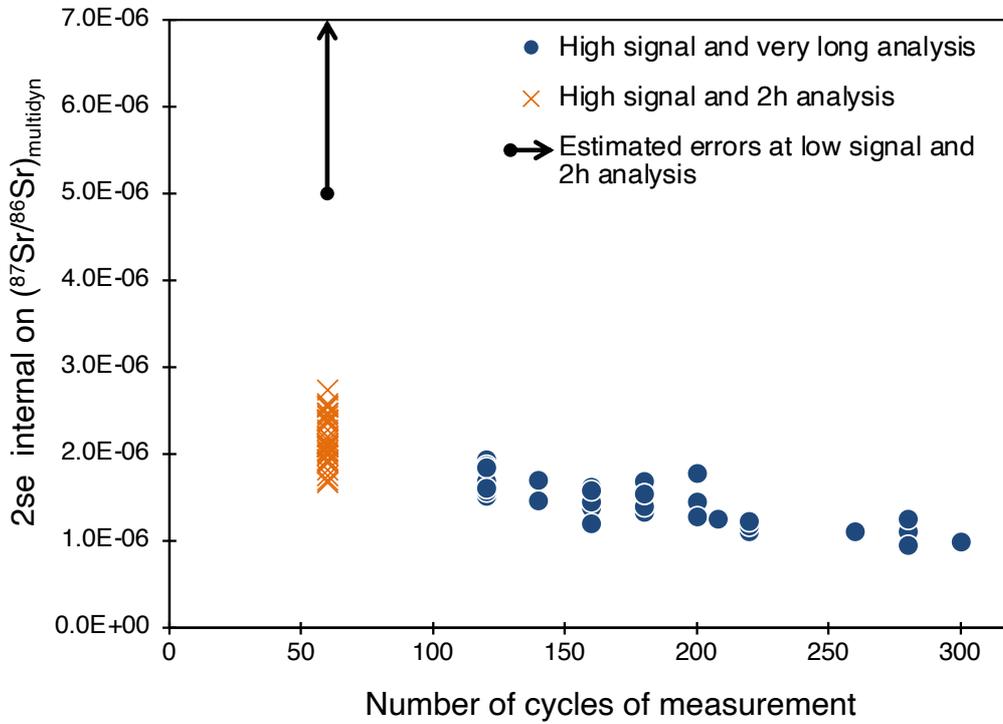


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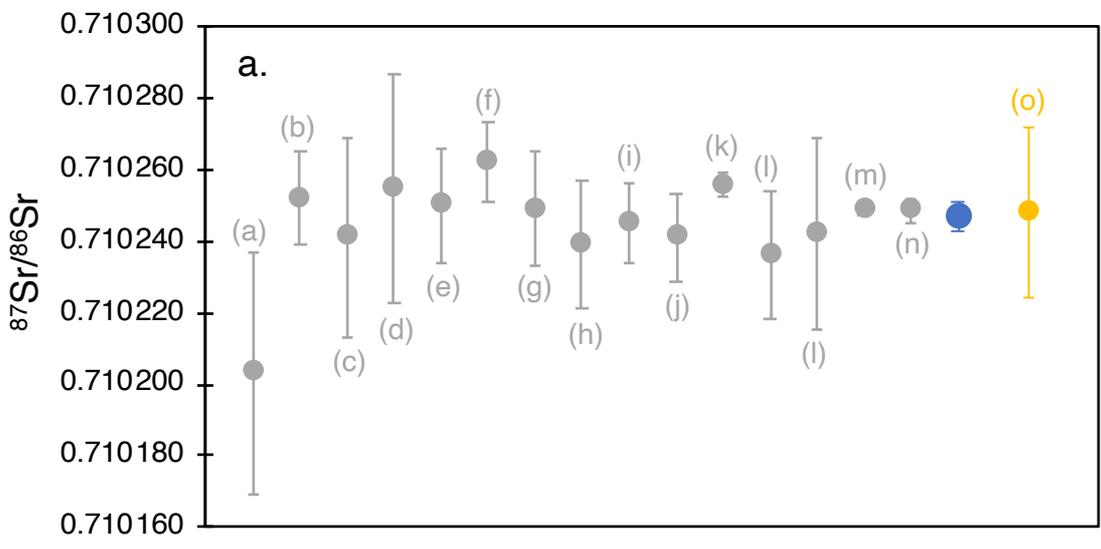
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681 **FIGURE 2:** Comparison between the internal errors typically obtained when running the Sr
 682 isotope analyses (i) with more than 10V of signal on $^{88}\text{Sr}^+$ for 6-7 hours (i.e. our standard
 683 conditions, blue dots) and (ii) with more than 10V of signal on $^{88}\text{Sr}^+$ for 2 hours only (orange
 684 crosses). An estimation of the internal errors obtained when running with less than 3V of signal
 685 for 2 hours is also shown for comparison (black arrow).
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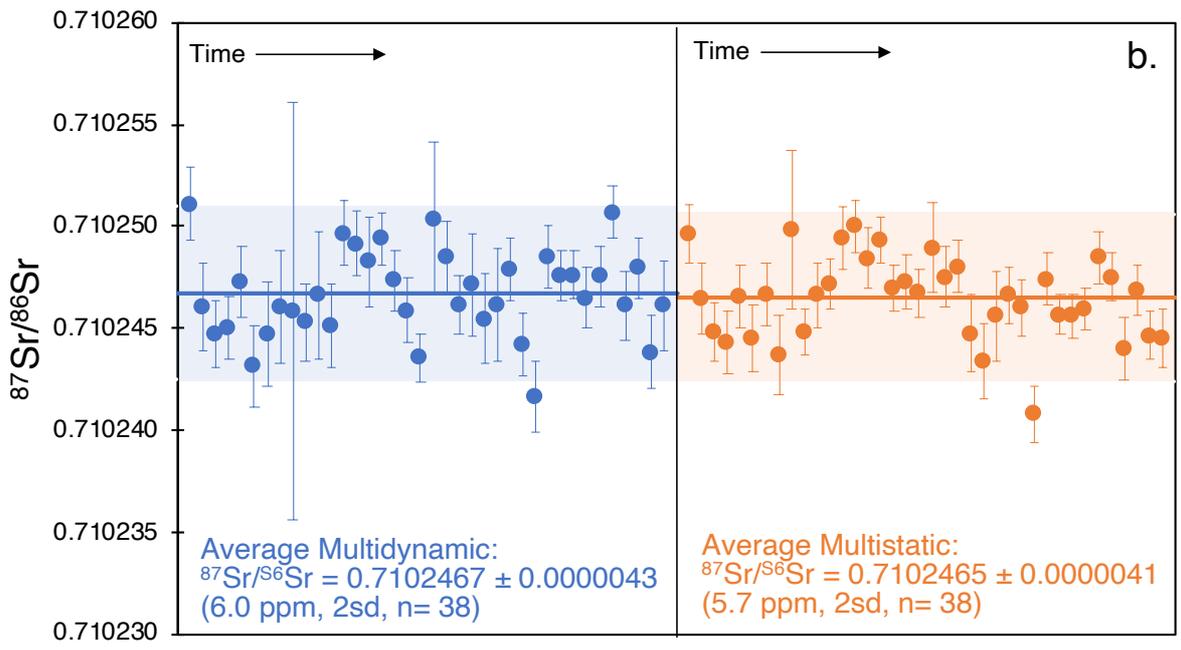


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689 **FIGURE 3:**
 690 a. Comparison of our mean $(^{87}\text{Sr}/^{86}\text{Sr})_{\text{multidyn}}$ (blue circle) with literature data (grey circles) for
 691 the pure Sr standard solution NBS 987. Note that the yellow circle corresponds to the
 692 recommended value reported by Zhang and Hu (2020) after a compilation of the data available
 693 in Georem. Error bars correspond to 2 sd. Literature: (a) Raczek et al. 2003, (b) Weis et al.
 694 2006, (c) Makishima et al. 2008, (d) Aciego et al. 2009, (e) Yang et al. 2010, (f) Chauvel et al.
 695 2011, (g) Yang et al. 2012, (h) Carpentier et al. 2014, (i) Li et al. 2014, (j) Pin et al. 2014, (k)
 696 Mokadem et al. 2015, (l) Fourny et al. 2016, (m) Yobregat et al. 2017, (n) Di et al. 2021, (o)
 697 Zhang and Hu 2020.
 698 b. Comparison between $(^{87}\text{Sr}/^{86}\text{Sr})_{\text{multidyn}}$ and $(^{87}\text{Sr}/^{86}\text{Sr})_{\text{multistat}}$ measured in the NBS 987
 699 standard solution over a period of ~ 10 months on the Nu TIMS. Error bars on individual data
 700 correspond to internal 2 se.
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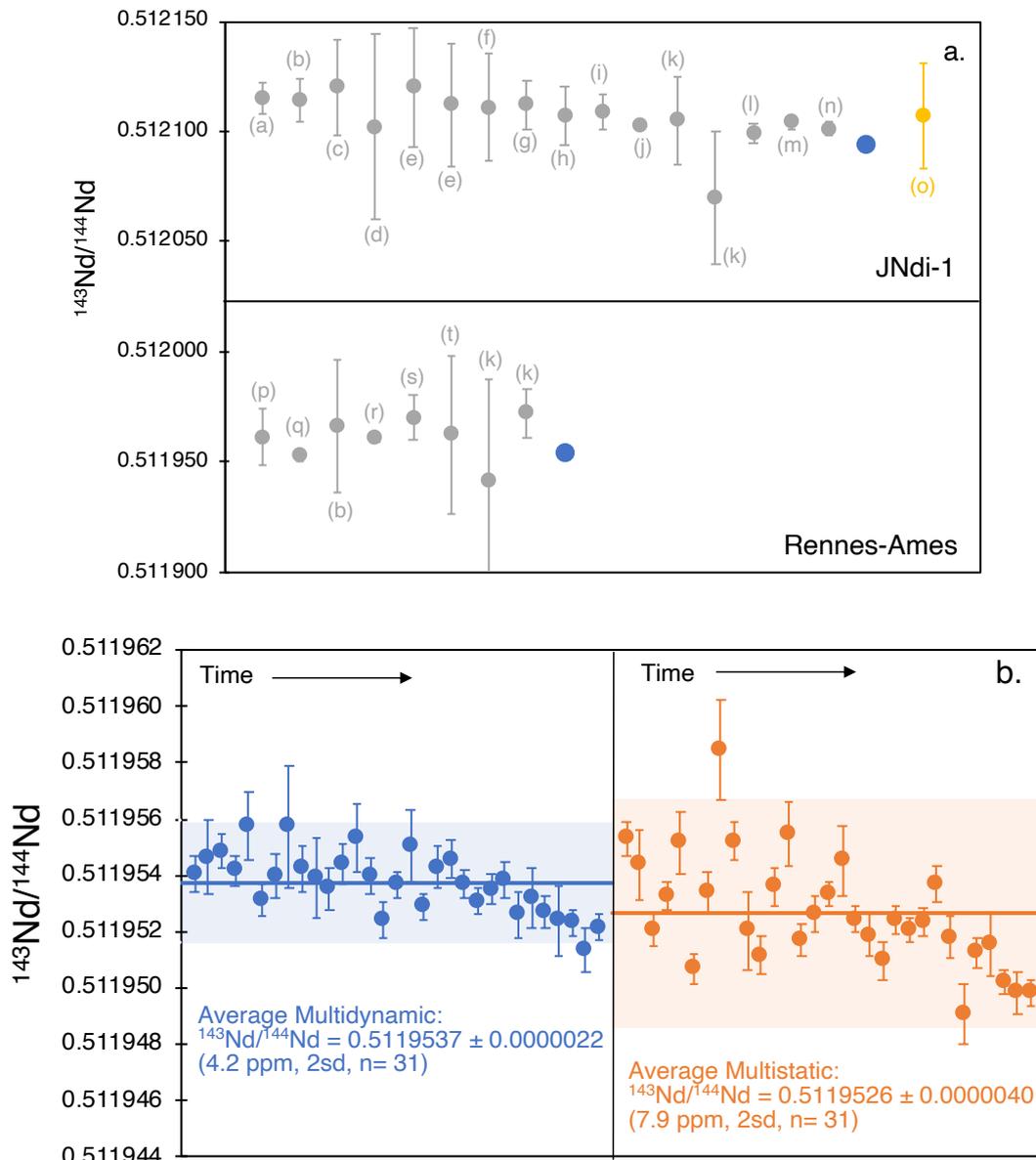


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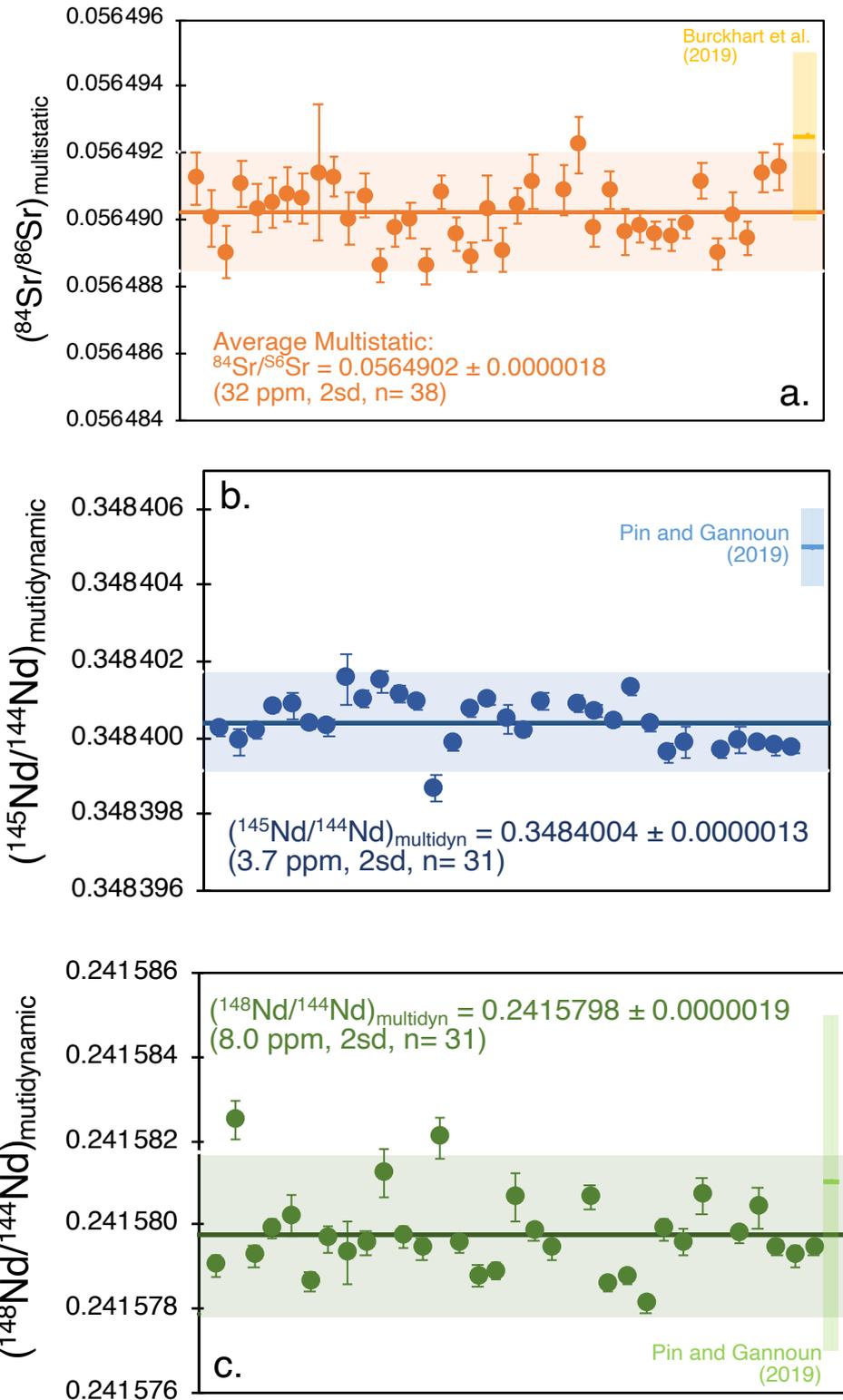
706 **FIGURE 4:**
 707 a. Comparison of our mean $(^{143}\text{Nd}/^{144}\text{Nd})_{\text{multidyn}}$ measured for the pure Nd standard solutions
 708 JNdi-1 and Rennes-Ames (blue circles) with literature data (grey circles). Note that we added
 709 the reference Fourny et al. (2016) for comparison, given the few data available in the literature
 710 for the Nd standard solution Rennes-Ames. Note that the yellow circle corresponds to the
 711 recommended value reported by Zhang and Hu (2020) after a compilation of the data available
 712 in Georem. Error bars correspond to 2 s.d. Literature: (a) Tanaka et al. 2000, (b) Le Fèvre and
 713 Pin 2005, (c) Li et al. 2007, (d) Aciego et al. 2009, (e) Chu et al. 2009, (f) Li et al 2011a, (g) Li
 714 et al 2011b, (h) Ali and Srinivasan 2011, (i) Li et al. 2014, (j) Pin et al. 2014, (k) Fourny et al.
 715 2016, (l) Garçon et al. 2018, (m) Pin and Gannoun 2019a, (n) Pin and Gannoun 2019b, (o)
 716 Zhang and Hu 2020, (p) Chauvel and Blichert-Toft 2001, (q) Caro et al. 2003, (r) Caro et al.
 717 2006, (s) Weis et al. 2006, (t) Chauvel et al. 2011.
 718 b. Comparison between $(^{143}\text{Nd}/^{144}\text{Nd})_{\text{multidyn}}$ and $(^{143}\text{Nd}/^{144}\text{Nd})_{\text{multistat}}$ measured in Rennes-Ames
 719 over a period of ~ 8 months on the Nu TIMS. Error bars on individual data correspond to
 720 internal 2 se.



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724 **FIGURE 5:**
 725 Stable Sr and Nd isotope compositions of the pure standard solutions NBS 987 (a) and Rennes-
 726 Ames (b-c) obtained in the course of this study. Error bars correspond to 2 s.e. For comparison
 727 are also plotted the latest high precision data (mean \pm 2 s.d.) from Burckhardt et al. (2019) and
 728 Pin and Gannoun (2019).
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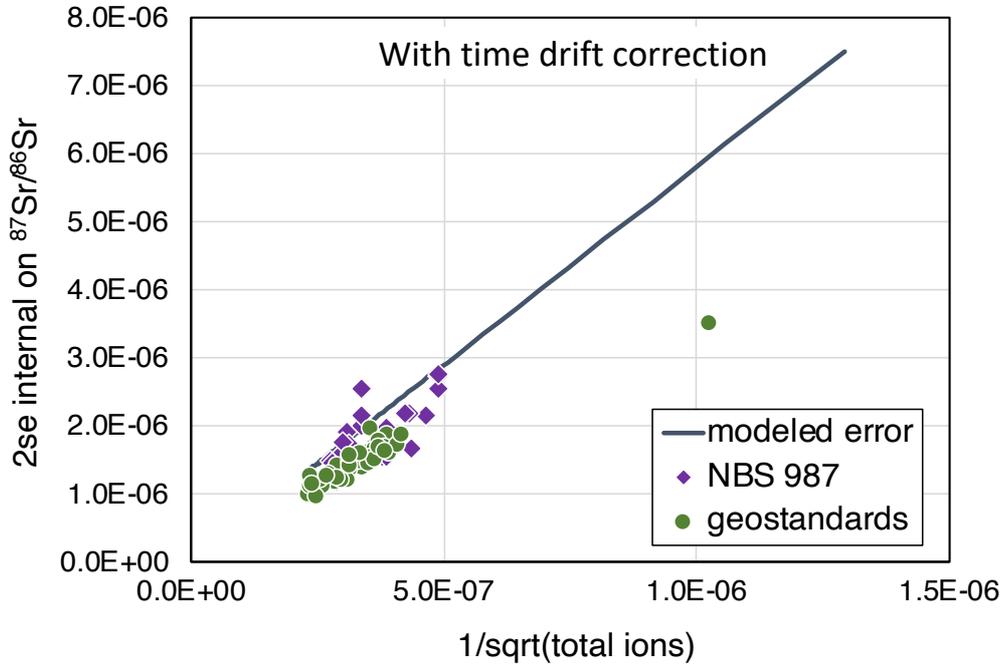


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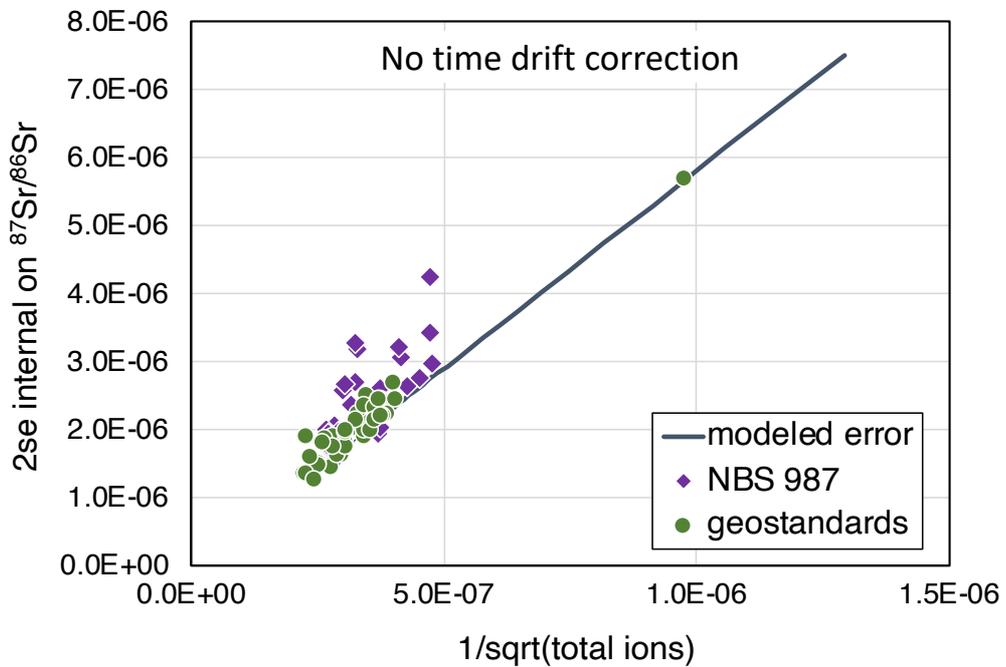
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733 **FIGURE 6:**
 734 Comparison between the theoretical precision modelled on multidynamic $^{87}\text{Sr}/^{86}\text{Sr}$ (blue line)
 735 and the actual uncertainties obtained for our analyses of NBS 987 (purple diamonds) and
 736 geostandards (green dots), with time drift correction (a) and without time drift correction (b).
 737

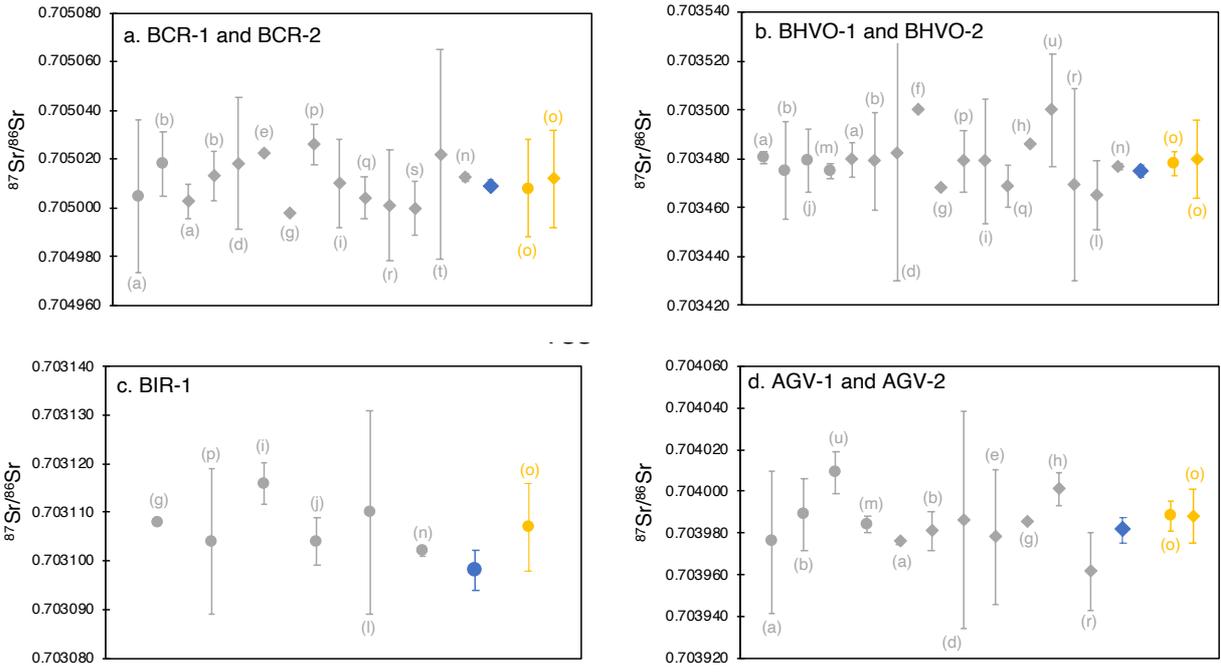


738 A.
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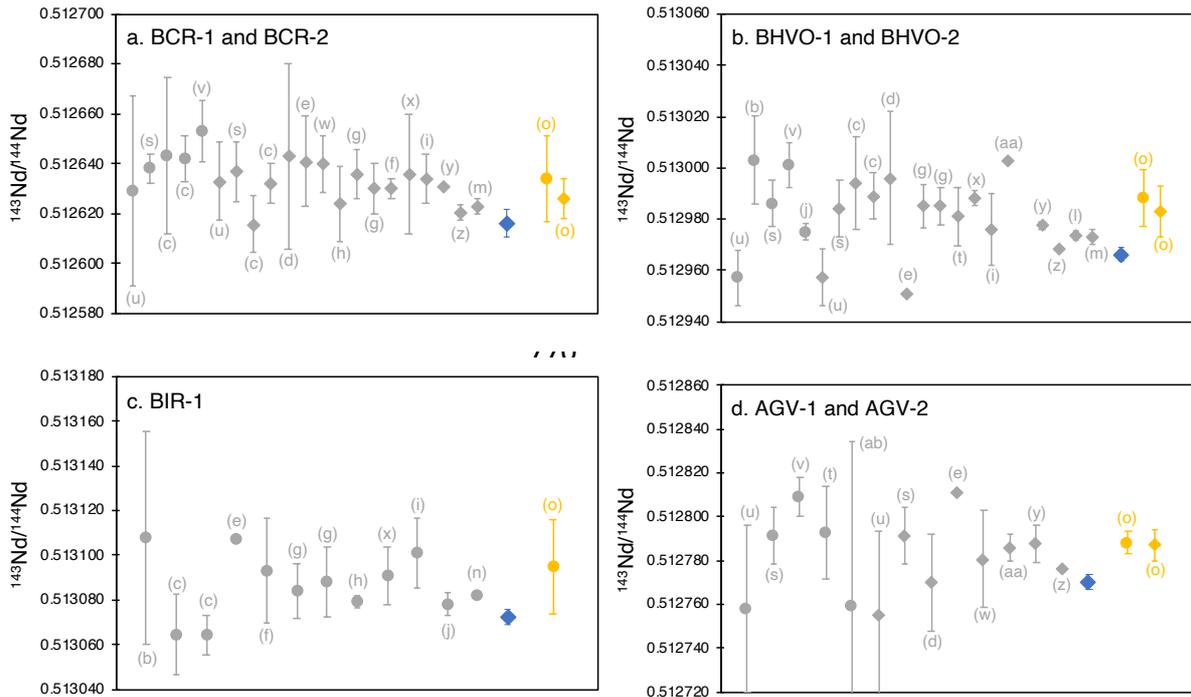
740 B.
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743 **FIGURE 7:**
 744 Multidynamic $^{87}\text{Sr}/^{86}\text{Sr}$ measured for different geostandards in the course of this study (blue
 745 symbols) and comparison with literature data (grey symbols). BCR-1, BHVO-1, BIR-1 and
 746 AGV-1 are represented as circles, while BCR-2, BHVO-2 and AGV-2 are represented as
 747 diamonds. Note that the data from Raczek et al. (2003) have been renormalized to 0.710248
 748 given the different $^{87}\text{Sr}/^{86}\text{Sr}$ they reported for NBS 987 compared to other studies (see Figure
 749 3a). Recommended values from Zhang and Hu (2020) are also shown for comparison (yellow
 750 symbols). Literature: (a-o) same as in figure 3a. (p) Li et al. 2012, (q) Neymark et al. 2014, (r)
 751 Klaver et al. 2015, (s) Jweda et al. 2016, (t) Fourny et al. 2019, (u) Koornneef et. 2015.
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759 **FIGURE 8:**
 760 Multidynamic $^{143}\text{Nd}/^{144}\text{Nd}$ measured for different geostandards in the course of this study (blue
 761 symbols) and comparison with the literature. BCR-1, BHVO-1, BIR-1 and AGV-1 are
 762 represented as circles, while BCR-2, BHVO-2 and AGV-2 are represented as diamonds.
 763 Recommended values from Zhang and Hu (2020) are also shown for comparison (yellow
 764 symbols). Literature: (a-t) same as in Figure 4a, (u) Raczek et al. 2003, (v) Mahlen et al. 2008,
 765 (w) Yang et al. 2010, (x) Li et al. 2012, (y) Klaver et al. 2015, (z) Li et al. 2015, (aa) Carpentier
 766 et al. 2014, (ab) Koornneef et al. 2015.
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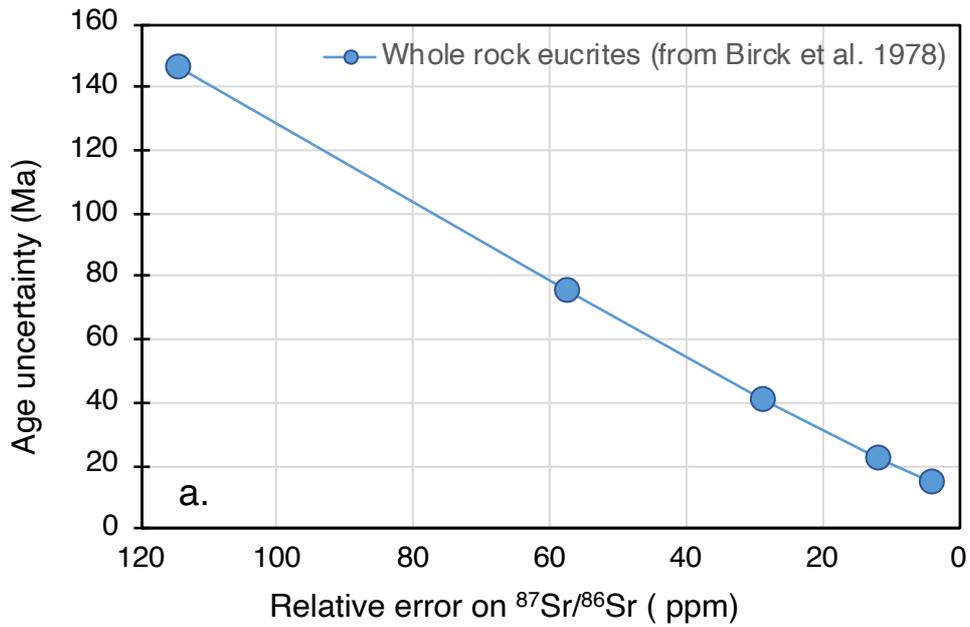
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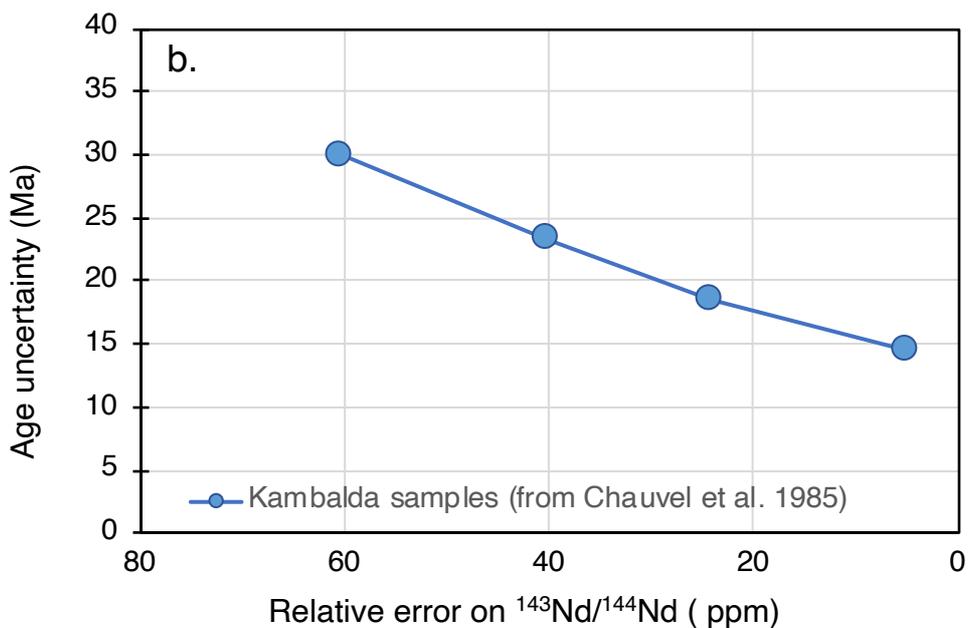
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775

776 **FIGURE 9:**
 777 a. Improvement on the uncertainty of the age determined from a Rb-Sr isochron with
 778 improvement of the precision on the $^{87}\text{Sr}/^{86}\text{Sr}$ for extraterrestrial materials (here for ~ 4.55 Ga
 779 old eucrites, Birck et al. 1978). We assumed an error of 1% on $^{87}\text{Rb}/^{86}\text{Sr}$ as stated in Birck et
 780 al. (1978).
 781 b. Improvement on the uncertainty of the age determined from a Sm-Nd isochron with
 782 improvement of the precision on the $^{143}\text{Nd}/^{144}\text{Nd}$ for terrestrial materials (here for 2.76 Ga old
 783 samples from Kambalda, Chauvel et al. 1985). We assumed an error of 0.2% on the $^{147}\text{Sm}/^{144}\text{Nd}$
 784 as estimated in Chauvel et al. (1985).
 785



786 A.



787 B.

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