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1 **Ar-Ar age constraints on the timing of Havre Trough opening and**
2 **magmatism.**

3

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26

27 **Abstract**

28 The age and style of opening of the Havre Trough back-arc system is uncertain due to a lack
29 of geochronologic constraints for the region. ⁴⁰Ar/³⁹Ar dating of 19 volcanic rocks from
30 across the southern Havre Trough and Kermadec Arc was conducted in three laboratories to
31 provide age constraints on the system. The results are integrated and interpreted as suggesting
32 that this subduction system is young (< 2 Ma) and coeval with opening of the continental

33 Taupo Volcanic Zone of New Zealand. Arc magmatism was broadly concurrent across the
34 breadth of the Havre Trough.

35

36 **Keywords**

37 Havre Trough, Kermadec Arc, Ar-Ar, magmatism, back-arc basin, rifting

38

39 **Introduction**

40 The present-day Kermadec Arc and associated Havre Trough back-arc basin is the youngest
41 in a series of Cenozoic volcanic arcs that have developed along the northern New Zealand
42 margin in response to convergence of the Pacific and Australian Plates (Mortimer et al.,
43 2010; Herzer et al., 2011; Bassett et al., 2016). The Kermadec Arc - Havre Trough (KAHT)
44 subduction system is the central portion of a contiguous arc system, with the Tonga Arc –
45 Lau Basin back-arc system to the north, and the Taupo Volcanic Zone (TVZ) of continental
46 New Zealand to the south (Figure 1) (Smith and Price, 2006). The predecessor to the
47 Kermadec Arc, the Miocene-Pliocene Colville Arc (Skinner, 1986; Ballance et al., 1999),
48 rifted apart in response to rollback of the Pacific Plate (Sdrolias and Muller, 2006; Wallace et
49 al., 2009), forming the Havre Trough and resulting in the establishment of the modern
50 Kermadec Arc front. The Colville Ridge and Kermadec Ridge are the remnants of the
51 Colville Arc (Figure 1).

52 The age of opening of the Havre Trough and establishment of the Kermadec Arc is
53 not clear owing to a paucity of age data. In part, this is due to the inherent difficulty in
54 obtaining reliable radioisotopic ages on young, glassy, and vesicular submarine volcanic
55 rocks with low potassium content, and in part due to tectonic complexity, and until recently,
56 limited seafloor sampling in the region. Here, we present ^{40}Ar - ^{39}Ar ages on seafloor volcanic
57 samples from across the southern KAHT subduction system that have important implications
58 for both the age and style of opening of the Havre Trough.

59

60 **Models for opening of the Havre Trough**

61 Several models have been proposed to explain the tectono-magmatic evolution of the Havre
62 Trough and Kermadec Arc, but the process and timing of opening remains contentious.

63 Malahoff et al. (1982), based on airborne magnetic studies and seismic lines over the
64 southern and central portions of the KAHT, tentatively interpreted the Havre Trough to be
65 undergoing spreading, centred on an axial ridge. They interpreted residual magnetic

66 anomalies to indicate a ca. 1.8 Ma age of opening of the basin. Wright (1993), however,
67 interpreted swath mapping data as showing that at least the southern Havre Trough lacked a
68 medial spreading ridge, and hence interpreted back-arc rifting rather than spreading as the
69 mode of extension. Further, Wright (1993), suggested that initiation of rifting occurred at ca.
70 5 Ma, although this age was constrained by extrapolation of geodetic data on continental New
71 Zealand rather than on direct age data from within the Havre Trough.

72 Subsequent models for Havre Trough opening agreed that the system was rifting but
73 have varied in the process and style of rifting being proposed. Wright et al. (1996) suggested
74 that Havre Trough opening and magmatism progressed eastward with time. Parson and
75 Wright (1996) further argued that there was a latitudinal progression from full oceanic
76 spreading in the Lau Basin to the north, to basin rifting in the TVZ to the south. The southern
77 Havre Trough was considered to be in an intermediate phase of rifting that was concentrated
78 along the axial zone of the trough. Ruellan et al. (2003), on the basis of multibeam
79 bathymetry and seismic reflection data, concluded that the southward propagation of
80 spreading was oversimplified, and that southward migration of subduction of the Louisville
81 Seamount Chain had effectively locked the KAHT. They proposed that opening of the Havre
82 Trough was initially fast and pervasive, and then relatively quiescent as the system became
83 locked. Wysoczanski et al. (2010), on the basis of morphological similarities, suggested that
84 the Havre Trough was in a similar state of rifting to the Valu Fa Ridge and Western Lau
85 Basin, and that it also was in a state of “disorganised spreading” (Martinez and Taylor, 2006)
86 whereby diffuse patches of extension localised in deep rifts precedes longitudinally traceable
87 axial ridges characteristic of true ocean spreading systems. This model reconciled the oceanic
88 spreading model of Malahoff et al. (1982) with models of rifting, and is similar to the Parson
89 and Wright (1996) final stage of rifting (their “Phase 4”) preceding full spreading.

90

91 **Analytical Methods and Results**

92 A total of 19 volcanic rocks of variable composition dredged from across the KAHT (Table
93 1) have been dated by Ar-Ar step heating. The sample set is diverse, including samples from
94 five arc front volcanoes, two volcanoes in the central Havre Trough (Gill and Rapuhia), a
95 deep central Havre Trough basin (Ngatoro Rift) with a short axial ridge in its southern extent,
96 and a cross-arc seamount chain (Rumble V Ridge) that spans the breadth of the Havre
97 Trough, from Rumble V to the Colville Ridge (Figure 2). Geochemical data for all the
98 samples have previously been reported, and the source of those data, together with new Ar-

99 Ar ages presented here, are shown in Table 1. With the exception of one andesite and one
100 dacite from the volcanic arc front, all samples are basalts or basaltic andesites (Figure 3).

101 Ar-Ar analyses were performed in three laboratories (USGS, Menlo Park; New
102 Mexico Institute of Mining and Technology (NMIMT), Socorro; and University of
103 Wisconsin-Madison), initially as four smaller and separate studies. The datasets are combined
104 here as one larger study to place constraints on the age of the KAHT (Table 1, Figure 2). All
105 ages presented in Table 1 include 2σ uncertainties and full details of the analytical techniques
106 are given in the Supplementary File.

107 The majority of ages for the arc front volcanoes are <0.06 Ma, although two samples,
108 from Clark (C/1) and Rumble III (X333) have slightly older mean ages of 0.11 Ma and 0.12
109 Ma respectively. Uncertainties on arc front samples however are large, with most ages having
110 2σ uncertainties of zero age, and most ages are zero within analytical uncertainty.

111 Three samples from Rumble V Ridge have ages of < 0.11 Ma, overlapping those of
112 the arc front volcanoes within uncertainty. The Ngatoro Rift samples have older ages
113 between 0.20 Ma and 0.68 Ma.

114 To the north, two samples from Rapuhia Ridge, a volcanic ridge extending southwest
115 from Rapuhia volcano in the centre of the Havre Trough, yielded ages of 0.05 ± 0.05 Ma and
116 0.11 ± 0.03 Ma. These ages are marginally older than, but within error of, ages derived from
117 the active volcanic arc front. They are on average younger than the samples from Rumble V
118 Ridge [see above], and notably younger than most of the Ngatoro Rift samples. Three
119 samples analysed from Gill volcano, a back-arc volcano in the Havre Trough that lies
120 between Rapuhia Ridge and the Colville Ridge (Figure 1), have ages significantly older than
121 all other samples, at 0.88 ± 0.05 Ma, 0.97 ± 0.03 Ma and 1.19 ± 0.04 Ma.

122

123 **Discussion**

124 The presented Ar-Ar ages are from samples that span almost the entire width of the southern
125 Havre Trough and thus provide important constraints on the manner and timing of its
126 opening.

127 A first order observation is that the oldest ages reported here, from a back-arc
128 stratovolcano (Gill volcano: Wysoczanski et al., 2010) in the western part of the Havre
129 Trough, are 0.9 - 1.2 Ma (Table 1, Figure 2). However, because Gill volcano sits on a rifted
130 basin floor, the implied age of rifting must be older. This age is similar to a preferred Ar-Ar
131 age of 1.1 ± 0.4 Ma reported for a basalt from the western Havre Trough (Mortimer et al.,

132 2007) sampled 450 km to the north of, and along strike from, Gill volcano, and to a $1.25 \pm$
133 0.06 Ma U-Pb zircon age from a tonalite xenolith from Raoul Island (Mortimer et al., 2010).
134 In addition, Mortimer et al. (2007) reported an Ar-Ar age of $1.2 \text{ Ma} \pm 0.8$ for a basalt from
135 the Northland Plateau (Figure 1), which they considered to be related to westernmost Colville
136 Ridge volcanism. Together, these ages show no evidence for magmatic activity in the Havre
137 Trough before c. 1.2 Ma, and as noted by Mortimer et al. (2010) suggest that magmatism was
138 active across the full width of the KAHT and west of the Colville Ridge at this time (Figure
139 2). Furthermore, one of our plateau ages from Gill volcano is 875 ± 50 ka, and thus it is
140 conceivable that the age of magmatism for the Havre Trough is younger than 1.2 Ma, and
141 possibly < 1 Ma.

142 Using the 19 new Ar/Ar ages presented in this study and two previously reported by
143 Mortimer et al. (2007; 2010), we now have sufficient geochronologic data to interpret the age
144 of the Havre Trough. In addition, Ballance et al. (1999) reported eight K-Ar ages of c. 2 Ma
145 or younger for the Kermadec Ridge and three K-Ar ages from the eastern Havre Trough,
146 which were near zero age (the oldest at 0.15 ± 0.12 Ma). These ages for the Havre Trough are
147 all significantly younger than the c. 5 Ma age of rifting proposed by Wright (1993). However,
148 we note that all current age data are from surficial seafloor volcanics, and future sampling
149 (especially from sub-seafloor drilling) may yield older ages that would require a
150 reinterpretation of the results presented here.

151 The young age of magmatism, if correct, provides three important implications for the
152 tectonic development of the Havre Trough.

153 Firstly, magmatism and translocation of the modern Kermadec Arc front did not occur
154 in a monotonic eastward progression. Notably, there is near- zero age arc magmatism in the
155 central portion of the Havre Trough at Rapuhia Ridge, and magmatism related to Rumble V
156 Ridge does not young to the east (Figure 4). The Rumble V Ridge dates are younger in age
157 than the Ngatoro Rift, indicating that the ridge may have been constructed over the Ngatoro
158 Rift (and if this is correct, also the Rumble Rift), rather than being cut by rifting as previously
159 suggested (Wright et al., 1996).

160 Second, reported age data for the Havre Trough is < 1.2 Ma, and possibly < 1 Ma.
161 This is younger than, but broadly consistent with, the 1.8 Ma age of rifting suggested by
162 Malahoff et al. (1982), although that model assumed a full spreading centre, whereas more
163 recent tectonic models based on seafloor morphology suggest that the Havre Trough is
164 comprised of a number of rifts and basal plateaus (e.g. Wright, 1993; Wysoczanski et al.,
165 2010; Wysoczanski and Clark, 2012). These ages infer a c. 2.5-4 x faster extension rate for

166 the Havre Trough than the 15-20 mm yr⁻¹ rate suggested by Wright (1993). An age of 2 Ma
167 would give an average rate of c. 40-50 mm yr⁻¹. Whilst reasonably fast, this rate is not
168 unusual for extension rates in other intra-oceanic back-arc rifts, and is still significantly
169 slower than the full ocean spreading rates of > 100 mm yr⁻¹ occurring in the Lau Basin and
170 Manus Basin (e.g. Taylor and Martinez, 2003; Heuret & Lallemand, 2005; Wallace et al.,
171 2005). Notably this is similar to the extension rate of c. 40-60 mm yr⁻¹ seen at the southern
172 portion of the Lau Basin (Parson and Wright, 1996; Martinez and Taylor, 2001).

173 Third, opening of the Havre Trough is coeval with initiation of TVZ magmatism and
174 rifting at c. 2 Ma (Wilson et al., 1995) and the TVZ rift and Havre Trough are the continental
175 and oceanic expression of the same rift system (e.g. Parson and Wright, 1996). It is unclear if
176 rifting was occurring prior to c. 2 Ma onshore in New Zealand: 1.8-3.9 Ma volcanism
177 occurred along the Maungatautari-Kaimai-Tauranga alignment parallel to but northwest of
178 the TVZ, as eruptions migrated southeast from the Coromandel area (Briggs et al., 2005).
179 Given our ages for the Havre Trough, and that the youngest reported age of volcanism from
180 the Colville Ridge is 2.6 Ma (Timm et al., in review), this magmatism is more likely to be
181 related to Colville Arc magmatism rather than Havre Trough magmatism.

182 The western portion of the TVZ is the oldest part of that system (the “old TVZ” of
183 Wilson et al., 1995, and Wilson and Rowland, 2016), and rifting is now focussed more to the
184 east and along a central rift, variously defined as the “young TVZ” and “modern TVZ”
185 (Wilson et al., 1995; Wilson and Rowland, 2016), Ruaumoko Rift (Rowland and Sibson,
186 2001) and the Taupo Rift (Villamor and Berryman, 2006). Whilst young arc magmatism is
187 broadly occurring across the Havre Trough (Figure 4) we have insufficient data to identify
188 any age progression of rift-related magmatism across the Havre Trough. It remains uncertain
189 if eastern Havre Trough rift magmatism is younger than western Havre Trough rift
190 magmatism, and so akin to the old and young/modern TVZ regions, respectively.

191 The present state of extension/rifting of the Havre Trough remains uncertain. In the
192 case of the Ngatoro Rift, the ages presented here indicate prolonged magmatism over at least
193 0.4 Ma, and that the rift is not presently magmatically active at the seafloor. Importantly
194 though there is extensive shallow seismic activity (< 13 km deep) within the Ngatoro Rift (de
195 Ronde et al., 2007). Regional moment tensor analysis for recent (2003-2012) shallow (< 33
196 km) earthquakes in the southern Havre Trough show extension as well as strike slip
197 movement (Ristau, 2014). At first order the shallow extensional seismicity in the Ngatoro
198 Rift and elsewhere in the Havre Trough indicates present-day extension / rifting of the
199 trough. Magmatic rift intrusives (e.g., dykes) may also be contemporaneous, however the

200 absence of present day surficial extrusives and lack of hydrothermal activity suggests that
201 seafloor, or near seafloor, rift magmatism is not occurring at the present day.

202

203 **Conclusions**

204 New Ar-Ar ages presented here, coupled with other published radioisotopic ages from the
205 literature (Ballance et al., 1999; Mortimer et al., 2007, 2010), suggest that opening of the
206 Havre Trough initiated < c. 2 Ma, and perhaps as recently as c. 1 Ma. The oldest ages occur
207 on the margins of the basin and significant young arc magmatism occurred across the central
208 Havre Trough. The timing of initiation of magmatism is coeval with that of the TVZ. The
209 caveat to our age constraints is that all samples are surficial and there are no ages for samples
210 within c. 25 km of the Colville Ridge (Figure 4).

211 Our results show that there has been arc and rift-related magmatism across the entire
212 southern Havre Trough within the last c. 1 Ma, both within rifts (e.g., Ngatoro Rift) and
213 constructing large stratovolcano cones such as Gill and seamounts of Rumble V Ridge
214 (Wright et al., 1996; Todd et al., 2010). This, together with the >4 km water depth in the
215 deepest parts of the basin, is more consistent with distributed rifting across the basin than
216 ocean spreading. Whether there are differences in age between rift-related magmas erupted at
217 different depths, or distance across the basin, or distance northward from New Zealand, is
218 important for understanding the tectonic evolution of the basin but remains to be discovered.
219 Our experience shows that $^{40}\text{Ar}/^{39}\text{Ar}$ ages can be obtained for the challenging Havre Trough
220 samples, but that sample selection and treatment are important considerations.

221

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369

370 **Figures**

371

372 Figure 1: Tectonic setting of New Zealand and the SW Pacific highlighting the Kermadec
373 Arc – Havre Trough (KAHT), the Tonga-Lau subduction system, and the Taupo Volcanic
374 Zone (TVZ) of continental New Zealand (red outline). Black arrow is the relative motion of
375 the Pacific Plate to a fixed Australian Plate for the southern KAHT region (DeMets et al.,
376 2010). HP = Hikurangi Plateau, Louisville SC = Louisville Seamount Chain, NP = Northland
377 Plateau, VFR = Valu Fa Ridge. Red triangles denote oceanic volcanoes of the Kermadec Arc
378 and Havre Trough, and the offshore TVZ (southernmost volcano, Whakatane). Highlighted
379 area is that of Figure 2.

380

381 Figure 2: Bathymetric map of the southern KAHT system, bounded by the Colville Ridge to
382 the west and the Kermadec Ridge to the east. Depths on the bathymetry scale are metres
383 below sea level, with depths < 1500 m shown as 1500 m and depths > 3500 m shown as 3500
384 m. Orange triangles are volcanoes: C = Clark, G = Gill, R = Rapuhia, RIII = Rumble III, RIV
385 = Rumble IV, RV = Rumble V, T = Tangaroa. Numbers in boxes denote new Ar/Ar ages
386 (Table 1).

387

388 Figure 3: Silica content of samples analysed in this study with distance from the crest of the
389 Kermadec Ridge.

390

391 Figure 4: Ar/Ar ages of Havre Trough samples (Table 1) with distance from the Kermadec
392 Ridge crest. Error bars show 2 sigma uncertainties. Black diamonds are K/Ar ages of
393 Ballance et al. (1999) from Kermadec Ridge and Havre Trough samples at least 300 km north
394 of samples presented here. Grey square at ~80 km is an Ar/Ar preferred age for a basalt from
395 the Havre Trough (Mortimer et al., 2007). Grey square at 0 km is a U-Pb age of zircon from a
396 tonalite from Raoul volcano (Mortimer et al., 2010), 600 km to the north of the study area,
397 where the modern arc front sits on the Kermadec Ridge (Figure 1).

398

399 **Table**

400

401 Table 1: Details of samples analysed in this study. Ages are: P=plateau ages, I=Isochron
402 ages, R=Recoil age (see Supplementary File for details). Supplementary File contains plateau
403 and isochron ages and plots, experimental data including K/Ca ratio, MSWDs, number of
404 steps, and total gas age; along with an explanation of experimental methods and machine data
405 for individual heating steps within each experiment. Results have been recalculated to a
406 consistent fluence monitor age equivalent to Fish Canyon sanidine at 28.198 Ma (Menlo
407 Park) and at 28.201 Ma (NMIMT). All errors are 2σ . For four samples, X379, X690, X682,
408 and X696 the mean age is negative, so the positive fraction of the age is reported as a
409 maximum value (i.e. <xx Ma), calculated as the mean of the 2σ error. IGSN numbers are
410 given for those samples that have been assigned numbers. Reference for geochemical
411 analyses: 1, Gamble et al, 1997; 2, Wright and Gamble, unpublished data; 3, Gamble et al.,
412 1993; 4, Todd et al., 2010; 5, Zohrab, 2017; 6, Todd et al., 2011. All geochemical data are
413 reported as anhydrous, with Fe as FeO_{total}.