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**Timing and development of sedimentation of the Cleaverville Formation and a
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Pilbara, Western Australia**

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25 **Abbreviated article abstract**

26 The Cleaverville Formation was deposited at ca. 3.1 Ga.

27 A strike-slip pull-apart basin formed in the Cleaverville area at 2.93 Ga.

28

29

30 **Abstract**

31 In the Cleaverville area of Western Australia, the Regal, Dixon Island, and Cleaverville

32 Formations preserve a Mesoarchean lower-greenschist-facies volcano-sedimentary

33 succession in the coastal Pilbara Terrane. These formations are distributed in a

34 rhomboidal-shaped area and are unconformably overlain by two narrowly distributed

35 shallow-marine sedimentary sequences: the Sixty-Six Hill and Forty-Four Hill Members

36 of the Lizard Hills Formation. The former member is preserved within the core of the
37 Cleaverville Syncline and the latter formed along the northeast-trending Eighty-Seven
38 Fault. Based on the metamorphic grade and structures, two deformation events are
39 recognized: D₁ resulted in folding caused by a collisional event, and D₂ resulted in
40 regional sinistral strike-slip deformation. A previous study reported that the Cleaverville
41 Formation was deposited at 3020 Ma, after the Prinsep Orogeny (3070–3050 Ma). Our
42 SHRIMP U–Pb zircon ages show that (1) graded volcanoclastic–felsic tuff within the
43 black shale sequence below the banded iron formation in the Cleaverville Formation
44 yields an age of (3114 ± 14) Ma; (2) the youngest zircons in sandstones of the Sixty-Six
45 Hill Member, which unconformably overlies pillow basalt of the Regal Formation, yield
46 ages of 3090–3060 Ma; and (3) zircons in sandstones of the Forty-Four Hill Member
47 show two age peaks at 3270 Ga and 3020 Ga. In this way, the Cleaverville Formation
48 was deposited at 3114–3060 Ma and was deformed at 3070–3050 Ma (D₁). Depositional
49 age of the Cleaverville Formation is at least 40–90 Myr older than that proposed in
50 previous studies and pre-dates the Prinsep Orogeny (3070–3050 Ma). After 3020 Ma,
51 D₂ resulted in the formation of a regional strike-slip pull-apart basin in the Cleaverville
52 area. The lower-greenschist-facies volcano-sedimentary rocks are distributed only

within this basin structure. This strike-slip deformation was synchronous with crustal-scale sinistral shear deformation (3000–2930 Ma) in the Pilbara region.

Keywords

banded iron formation, Cleaverville Formation, Cleaverville Syncline, coastal Pilbara Terrane, Mesoarchean, SHRIMP U–Pb zircon age, strike-slip pull-apart basin

1. Introduction

Archean greenstone belts are commonly affected by strike-slip deformation and contain strike-slip pull-apart basins along their structural boundaries (e.g., Kusky & Vearncombe, 1997). This strike-slip deformation in greenstone belts demonstrates the rigidity of the early continental crust. These belts record the final stages of continent formation and stabilization (e.g., Kusky & Vearncombe, 1997). The Pilbara Craton records strike-slip deformation during 2950–2900 Ma in the Kurrana and East Pilbara terranes and the West Pilbara Superterrane (Van Kranendonk, Smithies, Hickman, & Champion, 2007; Hickman, 2012). Examples of this deformation include the Lalla Rookh–Western Shaw structural corridor (Krapez & Barley, 1987; Zegers, de Keijzer, Passchier & White, 1998; Zegers, Wijbrans, & White, 1999; Zegers, Nelson, Wijbrans, & White 2001; Van Kranendonk & Collins, 2001; Van Kranendonk, 2008) and the

Whim Creek and Mallina basins alongside the Sholl Shear Zone (Krapez & Eisenlohr, 1998; Hickman, 2012). The Sholl Shear Zone in the West Pilbara Superterrane bounds the coastal Pilbara and Sholl terranes (Kriewaldt, 1964; Smith et al., 1998; Hickman, 1983, 2001, 2002, 2012). In this paper, we use the term “coastal Pilbara Terrane” for the Karratha and Regal terranes, bounded by the Sholl Shear Zone along its southern boundary (Kiyokawa, Taira, Byrne, Bowring, & Sano, 2002). The Sholl Shear Zone experienced major sinistral tectonism starting at 3020 Ma and was reactivated to produce dextral strike-slip faulting at 2990–2920 Ma (Barley, 1987; Smith et al., 1998; Blewett, 2002; Kiyokawa et al., 2002; Smith, 2003; Hickman, 2012, 2016). The Sholl Shear Zone truncates the coastal Pilbara Terrane and the Whim Creek Group (which formed in a pull-apart or back-arc basin setting) and the Whundo Group in the Sholl Terrane (e.g., Hickman, 2012; Hickman & Van Kranendonk, 2012).

In the coastal Pilbara Terrane, Kiyokawa et al. (2002) described a shallow sedimentary sequence (the Sixty-Six Hill and Forty-Four Hill Members of the Lizard Hills Formation) above a Mesoarchean greenstone sequence (Regal, Dixon Island, and Cleaverville Formations) in the Cleaverville area. Those authors identified three tectonic phases: D₁ folding and thrusting due to collision and accretion of an oceanic island arc and paleo-continent; D₂ left-lateral strike-slip deformation over a wide area;

and D₃ dextral strike-slip deformation localized along the Sholl Shear Zone. D₁ and D₂ were identified in the greenstone sedimentary and overlying shallow-water sequences in the Cleaverville area.

The Cleaverville Formation and its deformation are key to understanding the timing of the island-arc–continent accretion stage. It is important to establish the sedimentary environment, timing, and deformation of the Sixty-Six Hill and Forty-Four Hill Members of the Lizard Hills Formation, as these members represent post-accretion early-stage deformation and the final stabilization of the continental crust. We present new detrital SHRIMP zircon U–Pb ages for three samples, which constrain the sedimentation age of the Cleaverville Formation and the timing of D₁ and D₂ deformations of the coastal Pilbara Terrane.

2. Geological setting

In the coastal Pilbara Terrane, the areas of Cleaverville beach and Dixon Island (Figure 1) comprise a greenschist-facies volcanoclastic sequence (the Dixon Island, Cleaverville, and Regal Formations) and a well-preserved quartz-rich sandstone sequence (Lizard Hills Formation; Kiyokawa & Taira, 1998). The low-grade rocks in the Cleaverville area have been examined previously (Ohta, Maruyama, Takahashi, Watanabe, & Kato, 1996; Hickman, 1997, 2001, 2002, 2012, 2016; Kiyokawa & Taira, 1998; Kiyokawa et

al., 2002; Van Kranendonk et al., 2007; Shibuya, Kitajima, Komiya, Terabayashi, & Maruyama, 2007). In the Cleaverville area, the volcanoclastic sequence comprises, from bottom to top, the Lagoon Formation (here termed the Lagoon Member), the Lagoon Pillow Basalt (or Regal Formation; Hickman, 2001, 2002), the Dixon Island Formation (Kiyokawa et al., 2006; Kiyokawa, Ito, Ikehara, Yamaguchi, Koge, & Sakamoto, 2012a), the Port Robinson Basalt (Kiyokawa, Koge, Ito, & Ikehara, 2014), and the Cleaverville Formation (Kiyokawa & Taira, 1998; Kiyokawa et al., 2002). The age of the upper Dixon Island Formation has been constrained to 3195 ± 12 Ma based on the U–Pb zircon age of a silicic tuff (Kiyokawa et al., 2002).

A fold axis (the Cleaverville Syncline) has been identified in the Cleaverville Formation and Lagoon Pillow Basalt (Kiyokawa & Taira, 1998; Kiyokawa et al., 2002). Two shallow-water sedimentary sequences of the Lizard Hills Formation unconformably overlie the northern part of the Lagoon Member along the Cleaverville Syncline axis and the eastern edge of the Lagoon Pillow Basalt, and are termed the Sixty-Six Hill and Forty-Four Hill Members (Kiyokawa & Taira, 1998; Kiyokawa et al., 2002, 2012a).

Regarding the stratigraphic nomenclature in the Cleaverville area, we mostly follow the maps published by the Geological Survey of Western Australia (e.g.,

Hickman, 2001, 2002, 2016) but use the member names from Kiyokawa and Taira (1998) and Kiyokawa et al. (2012a).

3. Stratigraphy

In this section, we describe the lower-greenschist-facies volcano-sedimentary sequences and the overlying cover sedimentary sequences (Figure 2). This stratigraphy is based mainly on Kiyokawa & Taira (1998), together with our new data.

3.1 Basement greenstone belt

The Regal Formation is divided into the Lagoon Member and Lagoon Pillow Basalt (Kiyokawa & Taira, 1998). To the southeast of the Cleaverville area, the Lagoon Pillow Basalt is overlain by quartz sandstones of the Forty-Four Hill Member, across a marked angular unconformity.

The Dixon Island Formation is exposed mainly on the northern coast of Dixon Island and represents a hydrothermal vent system that formed in a deep oceanic environment (Kiyokawa, Ito, Ikehara, & Kitajima, 2006; Kiyokawa et al., 2012a). The upper part of this formation was drilled by the DXCL Project to collect DX core (Yamaguchi, Kiyokawa, Ito, Ikehara, Kitajima, & Suganuma, 2009; Kiyokawa, Koge, Ito, Ikehara, Kiyajima, Yamaguchi, & Suganuma, 2012b).

The Cleaverville Formation is well preserved along the western part (Cleaverville A area) and eastern part (Cleaverville F area) of Cleaverville beach (Figure. 1). The Cleaverville Formation comprises the Black Chert and Banded Iron Formation (BIF) Members.

The Black Chert Member is generally poorly exposed and comprises highly weathered white–pink shales and chert-like rocks cropping out along the beach. Using the 1:500 map of the Cleaverville A area compiled by Kiyokawa & Taira (1998), we found well-preserved bedded volcanoclastic–felsic tuff in the upper part of the Black Chert Member (Figure 3a and b). These rocks form 3-m-thick deposits in channels that are a few meters wide. Yellow volcanic and black chert fragments are present within a yellow, fine-grained, silicic volcanoclastic matrix near the base of the bed and fine laminated felsic tuff near the top. In the Cleaverville F area at a site 7 km from the Cleaverville A area, a 50-cm-thick fine-grained felsic tuff is found at the same stratigraphic level. This volcanoclastic–felsic tuff is a key bed and dateable layer in the Black Shale Member. We sampled the yellow, silicic volcanoclastic–felsic tuff at Cleaverville A area for zircon U–Pb dating.

The BIF Member comprises well-bedded shale and BIF at topographic highs. The BIF is interbedded with 10-cm-thick shale and chert beds, which thicken gradually to 50

cm over a lateral distance of 50–100 m. The upper part of the BIF Member is separated from the Sixty-Six Hill Member by a fault, which trends east–west through a narrow linear topographic depression (i.e., a fault) in the center of Sixty-Six Hill.

3.2 Cover sequence

3.2.1 Sixty-Six Hill Member

The Sixty-Six Hill Member is found in the core of the Cleaverville Syncline, along the horizontal fold axis, and tightly folded between the Lagoon Pillow Basalt and the BIF Member. The southern boundary might be an unconformable contact with the Lagoon Pillow Basalt, and the northern boundary may be in faulted contact with the BIF Member.

We identified four stratigraphic units: basal, lower, middle, and upper (Figure 2; based on Kiyokawa & Taira, 1998). The basal unit is a poorly sorted, black chert and pebble-rich conglomerate (Figure 3c and d). The lower unit consists of laminated chert, volcanoclastic rock, and pebbly sandstone. The middle unit includes laminated black (Figure 3e) and white–black cherts. The upper unit comprises cross-bedded, coarse-grained, well-sorted, quartz–plagioclase sandstone (Figure 3f) in 20–50-cm-thick beds (Figure 4a and b). The cross-bedding indicates that the younging direction is to the north on the southern limb of the syncline.

3.2.2 Forty-Four Hill Member

The Forty-Four Hill Member is preserved at the eastern boundary of the Lagoon Pillow Basalt and Nicol Well subcomplexes and crops out along two parallel northeast-trending ridges (Forty-Four Hill and Eighty-Seven Hill; Figure 1). In the northwest, this member is composed of well-sorted quartz sandstones. The member contains southeast-dipping beds and overlies the Lagoon Pillow Basalt via an angular unconformity along an erosional contact. This member has been identified as part of the Nickol River Formation (Hickman, 2016). However, based on the stratigraphy, structure, and zircon ages of this member, we identified younger sedimentary sequence than the Nickol River Formation (Kiyokawa & Taira, 1998; Kiyokawa et al., 2002).

There are four main units in the Forty-Four Hill Member (Kiyokawa & Taira, 1998). The basal unit is a 30-m-thick conglomerate containing black quartzite pebbles, which unconformably overlies weathered pillow basalt of the Lagoon Pillow Basalt. The lower unit comprises a cross-bedded sandstone (with herring-bone cross-beds) containing well-rounded quartz grains and black quartz pebbles (Figure 3g). This unit is 100 m thick and forms the northeast-trending ridges of Forty-Four Hill (Figure 1). The middle unit is 120 m thick and comprises poorly sorted, brownish-red, mud-rich sandstones that conformably overlie the lower sandstone units (Figures 3h and 4c), and

thin dolomite layers (Kiyokawa & Taira, 1998). This unit is located in a topographic depression along Forty-Four Hill and Eighty-Seven Hill. The upper unit at Eighty-Seven Hill (Figure 1) is folded and comprises an 80-m-thick sequence of bedded white chert, shale, and thin volcanic rocks. The banded white chert is only found in the southeastern part of Eighty-Seven Hill, which is located along the Eighty-Seven Hill Fault (Figure 1).

4. Structures

A lower-greenschist-facies volcanic–sedimentary sequence crops out in a rhomboidal-shaped area of ~12 km by ~7 km covering Cleaverville beach and Dixon Island (Figure 1). This sequence is bounded by upper-greenschist-facies to lower-amphibolite-facies rocks of the Nickol Well and Regal subcomplexes (Kiyokawa et al., 2002). We describe the Cleaverville Syncline and the margins of the rhomboidal-shaped area (northwestern, southern, and southeastern boundaries) in the following sub-sections.

4.1 Cleaverville Syncline

The Cleaverville Syncline is asymmetrical and it contains the Dixon Island and Cleaverville Formations in the northern limb, and the Lagoon Pillow Basalt in the southern limb. The Sixty-Six Hill Member occurs in the fold core (Kiyokawa & Taira, 1998). In the western part of the Sixty-Six Hill area, a tight fold is observed in the

214 Lagoon Pillow Basalt. The eastern part of the fold axis is parallel to an E–W-trending
215 fault. Based on a stratigraphic reconstruction, the total thickness of the Regal, Dixon
216 Island, and Cleaverville Formations is >3–5 km (Kiyokawa & Taira, 1998). However,
217 prior to folding the combined thickness of these formations differed by >800 m in the
218 areas that became the northern and southern limbs of the fold.

219 We propose that the Cleaverville Syncline was formed in four steps (Figure 5),
220 assuming the stratigraphy of this area is consistent spatially (i.e., the Regal, Dixon
221 Island, and Cleaverville Formations from base to top). First, north-verging asymmetric
222 folding occurred after deposition of the Dixon Island and Cleaverville Formations.
223 Second, northward thrusting resulted in the Regal Formation, to the south of the hinge,
224 being moved to a higher stratigraphic position. Along the fold axis, top-to-north
225 thrusting took place and erosion removed >1000 m of the Dixon Island and Cleaverville
226 Formations. The different stratigraphy in the two limbs of the fold might have resulted
227 from top-to-the-north thrusting during the asymmetric folding that formed the
228 Cleaverville Syncline. Third, erosion led to an unconformity between the Sixty-Six Hill
229 Member and Lagoon Pillow Basalt, related to the thrusting and folding (D_1). Finally,
230 further tight folding took place during regional sinistral strike-slip deformation (D_2).
231 Based on the strain ellipsoid of the sinistral deformation, the orientation of the

232 Cleaverville Syncline was also affected by compression during D₂ strike-slip
233 deformation.

234 **4.2 Margins of the rhomboidal-shaped area**

235 **4.2.1 Northwestern boundary**

236 The northwestern boundary of the rhomboidal-shaped area is located offshore from
237 Cleaverville, between the Cleaverville coast and Walcott Island (Figure 1). Walcott
238 Island is <1 km from Cleaverville beach and hosts amphibolite- to upper-greenschist-
239 facies pillow and massive basalts. Metamorphic grade changes markedly along the
240 coast. Sinistral deformation structures (asymmetric faults and shear zones) are observed
241 within the Cleaverville Formation in the Cleaverville A area (Kiyokawa et al., 2002).
242 We identified a SE-dipping, sinistral transtensional fault in the ocean area between
243 Cleaverville beach and Walcott Island (Figure 1; Kiyokawa et al., 2002).

244 **4.2.2 Southern boundary**

245 The southern boundary of the rhomboidal-shaped area, between the Regal Formation
246 (Lagoon Member) and the Karratha Supercomplex, is poorly exposed (Figure 1).
247 Lower-greenschist-facies metavolcanic rocks of the Lagoon Member are in contact with
248 the strongly foliated metasedimentary rocks of the Lydia Mine Complex (Kiyokawa &

Taira, 1998; Figure 1). The contrasting metamorphic grade and foliation trend across the boundary indicate a fault contact.

4.2.3 Southeastern boundary: the strike-slip Eighty-Seven Hill Fault

The linear topography on the southeastern margin of Eighty-Seven Hill, the SE-dipping beds of the Forty-Four Hill Member, and the amphibolite pillow basalt of the Nicol Well complex indicate that a NW-dipping normal fault (the Eighty-Seven Hill Fault; Figure 1) runs along the southeastern side of Eighty-Seven Hill. This fault separates lower-greenschist-facies rocks from lower-amphibolite-facies rocks (Kiyokawa et al., 2002).

A basalt block with pillow lava identical to the Lagoon Pillow Basalt is found in the central-southern area between Forty-Four Hill and Eighty-Seven Hill (Figure 1; Kiyokawa & Taira, 1998). Given the younging direction, this block has been rotated 90° clockwise from the orientation of the Lagoon Pillow Basalt (Kiyokawa & Taira, 1998). The distribution of the SE-dipping sedimentary sequence, the presence of silicified rock along the Eighty-Seven Hill Fault and the occurrence of the rotated block indicate sinistral transtensional deformation.

5. Zircon U–Pb dating

We obtained new zircon U–Pb ages from the Cleaverville Formation and the Lizard Hills Formation. We interpret the ages for the volcanoclastic rocks from the Cleaverville Formation to represent the depositional age. We also obtained an age for detrital zircons from well-sorted sandstones from the upper part of the Sixty-Six Hill Member, and from brownish-red sandstones from the middle part of the Forty-Four Hill Member.

5.1 Analytical methods

Rock samples were cleaned with deionized water in an ultrasonic bath for >5 min, and zircons for U–Pb analysis were separated using magnetic and heavy liquid (1,1,2,2-tetrabromoethane and methylene iodide) techniques at Kyushu University, Japan. Zircons were handpicked to ensure that the selected grains were representative of the zircon population as a whole. Zircon grains were mounted in an epoxy resin disc together with the reference material OG-1 (Stern, Bodorkos, Kamo, Hickman, & Corfu, 2009). The discs were polished to reveal cross-sections through grain centers. Backscattered electron (BSE) and cathodoluminescence (CL) images were obtained using a JEOL JSM-5900LV scanning electron microscope (SEM) with a Gatan mini-CL detector to characterize internal zoning patterns and identify suitable analytical points within each zircon grain. Subsurface mineral inclusions and cracks were identified using

an optical microscope with transmitted light. Prior to analysis by a sensitive high-resolution ion microprobe (SHRIMP-II), the surface of the grain mount was washed with dilute HCl and ultrapure water, and then coated with gold.

Zircon U–Pb analyses were conducted on the SHRIMP-II housed by the National Institute of Polar Research (NIPR), Tokyo, Japan. An O_2^- primary ion beam of 3.9 nA was used to sputter an analytical spot of 25 μm in diameter on each polished zircon grain. A primary ion beam of 1.1 nA was used for the Cleaverville A area sample, with a spot diameter of 10 μm . We followed the procedure for Pb and U isotopic analyses described by Horie, Takehara, Suda, & Hidaka (2013). We used reference materials FC1 ($^{206}Pb/^{238}U$ age = 1099 Ma; Paces & Miller, 1993) and SL13 (U = 238 ppm; Claoué-Long, Compston, Roberts, & Fanning, 1995) to calibrate the $^{206}Pb/^{238}U$ ratios and U concentrations in zircons, respectively. The OG1 zircon ($^{207}Pb/^{206}Pb$ age = 3465 Ma; Stern et al., 2009) was also periodically analyzed with the FC1 zircon to confirm the U/Pb calibration and instrumental mass fractionation of Pb isotopes. U–Pb data were reduced following the method of Williams (1998), using the SQUID2 add-in for the Microsoft Excel macro developed by Ludwig (2009). Common Pb was corrected using the measured ^{204}Pb and the model for common Pb compositions proposed by Stacey and Kramers (1975). The pooled ages presented in this study were calculated after

correction for common Pb, using Isoplot/Ex software (Ludwig, 2012). The analytical uncertainties listed in Table 1 and plotted on the concordia diagrams are at the 1σ level and include measurement errors and uncertainties in the common Pb corrections.

5.2 Age of the Black Shale Member of the Cleaverville Formation

We collected graded volcanoclastic–felsic tuff from the middle part of the Black Shale Member of the Cleaverville Formation (Figure 1; Cleaverville A area graded volcanoclastic–felsic tuff; C911 section; sampling location 20°39'51.6"S, 116°58'53.4"E). More than 40 kg of sample was collected from the C911 section from which we obtained only 46 zircon grains. The zircons are euhedral or rounded, and fine-grained ($> 100 \mu\text{m}$); most are pink to clear in color and crack-free. We obtained 46 analyses from 43 zircons, and 17 grains had concordant ages. Eleven euhedral zircons yielded a mean age of 3110 Ma, whereas rounded metamict zircons yielded discordant ages between 3700 Ma and 3200 Ma. SEM and optical microscope observations after the SHRIMP analyses indicated Pb loss at spots C91121-02.1 and C91127-03.1 caused by the alteration of zircon (Takehara, Horie, Hokada, & Kiyokawa, 2018). Therefore, we interpret the ages of the youngest nine zircons to represent the age of the graded volcanoclastic–felsic tuff of (3114 ± 14) Ma (Mean sequence weighted deviation: MSWD = 1.6; Figure 6a and b).

5.3 Age of the Sixty-Six Hill Member

We dated the upper part of a well-sorted, medium-grained, quartz–plagioclase arenitic sandstone (sampling location 20°39'38.9"S, 117°00'45.2"E). The samples contain rounded zircon grains that are 100–200 µm long. We collected 89 grains (all concordant) from sample 100912-14 (Figures 3f and 4a) and 106 grains (100 concordant) from sample 100912-15 (Figure 4b). The age results for both samples of detrital zircons fall into two major groups at 3100–3050 and 3300–3200 Ma, along with a minor group at 3700 Ma (Figure 6c and d).

5.4 Age of the Forty-Four Hill Member

We sampled poorly sorted, brownish-red, quartz-rich sandstones with a mud matrix (sampling location 20°41'14.0"S, 117°01'11.5"E) from the middle unit. The zircon grains are rounded and 50–100 µm long. We analyzed 64 spots on 60 zircons from sample 100912-28 (Figures 3h and 4c), and 23 spots yielded concordant ages, with 41 spots being discordant. The zircons from sample 100912-28 cluster into two age groups at 3280–3200 and 3030–3020 Ma (Figure 6c and d).

6. Implications for the timing of sedimentation and tectonism

A D₂ structural map of the coastal Pilbara Terrane is shown in Figure 7. The Cleaverville area contains a clearly defined, rhomboidal-shaped area of lower-

greenschist-facies metamorphic rocks. This map also demonstrates that D₁ (i.e., Cleaverville Syncline formation) and D₂ (i.e., strike-slip deformation) represent distinct deformational stages. The Forty-Four Hill Member was identified along the northeast-trending fault system, parallel to the volcanic rocks of the Fortescue Group. The map also shows the sinistral deformation of the Princep fold axis and western part of the Regal Formation. In addition, most of the lithological subcomplexes that are divided by several mylonitic zones converge into the Sholl Shear Zone (Kiyokawa et al., 2002).

Our new age data for the Cleaverville Formation and the Sixty-Six Hill and Forty-Four Hill Members are important for improving our understanding of the depositional age of the Cleaverville Formation, and the timing of collision, continental reworking, and strike-slip pull-apart basin formation associated with D₂ strike-slip faulting. We are able to constrain the sedimentation and deformation history in the Cleaverville area using our new age data, integrated with previous studies of sedimentation in the central and eastern Pilbara (Figure 8). These data constrain the D₁ to D₂ deformation phases of Kiyokawa et al. (2002) and enable us to present a detailed history of the sedimentation and tectonic development.

6.1 Depositional age of the Cleaverville Formation

The depositional age of the lower part of the Dixon Island Formation is (3195 ± 12) Ma (Kiyokawa et al., 2002), and the new age of the upper part of the Black Shale Member is (3114 ± 14) Ma, which represents the maximum depositional age. Both ages were determined on samples from thin volcanic and tuff beds.

Nelson (1998) reported zircon ages of 3022 Ma and 3060 Ma for volcanoclastic rocks described as being part of the Cleaverville Formation (sample number 127330; sampling location $20^{\circ}39'34''\text{S}$, $117^{\circ}01'20''\text{E}$; Figure 1). This sample location, now identified as from the lower unit of the Sixty-Six Hill Member, and the age accuracy is not well constrained. Our sandstone age data from the upper part of the Sixty-Six Hill Member are dominated by 3060 Ma detrital grains. As such, the uppermost Cleaverville Formation must be older than 3060 Ma. Detrital zircon grains with ages of 3090–3060 Ma in the Sixty-Six Hill Member might be related to the initial stage of Cleaverville Syncline formation after deposition of the Cleaverville Formation. Deposition of volcanoclastic rocks within the Sixty-Six Hill Member and Cleaverville Syncline deformation were related to D_1 island arc accretion.

Therefore, we consider that sedimentation of the Cleaverville Formation started at 3120 Ma and ended prior to 3090–3060 Ma. This formation was then continuously

deformed during 3060–3020 Ma, coeval with the Prinsep Orogeny. The new age is 40–80 Myr older than previous estimates of the sedimentation age (Smithies & Farrell, 2000; Blewett, 2002; Hickman, 2016) of the BIF of the Cleaverville Formation.

In addition, the 3105 Ma depositional age for the Nimingarra Iron Formation in the Shay Gap belt from the East Pilbara Terrane (Sheppard, Krapez, Zi, Rasmussen, & Fletcher, 2017) is similar to our age for the Cleaverville Formation. However, the 3105 Ma age of the Nimingarra Iron Formation is uncertain because the youngest zircon was dated at 3027 Ma, and the spread of zircon ages used in the calculation was 120 Myr.

Despite the uncertainties, the 3110–3060 Ma sedimentation age is important for constraining the accretion and amalgamation of the coastal Pilbara Craton. It is apparent that a BIF was deposited over a more regionally extensive area than previously thought.

6.2 Characteristics of the strike-slip pull-apart basin

The rocks of the Regal, Dixon Island, and Cleaverville Formations have been affected by prehnite–pumpellyite–lower-greenschist-facies metamorphism. At these grades, the rocks experienced temperatures of 250–350 °C and pressures of 2–7 kbar (Kiyokawa et al., 2002). Beyond the outcrops of the Cleaverville low-grade rocks, the rocks are upper greenschist–lower amphibolite-facies, indicating temperatures of 400–550 °C and pressures of 3–10 kbar. This shows that the Cleaverville low-grade rocks experienced

temperatures 150–200 °C lower than those of the surrounding rocks. If the geothermal gradient was double the modern value ($2\text{--}4 \times 10^{-2}$ °C/m; Martin, 1986), then this suggests that the strike-slip pull-apart basin generated 2000–4000 m of vertical offset. Most of the sediments containing clastic rocks of continental origin are now only preserved in the Forty-Four Hill Member along the fault due to erosion, which has exposed the basement greenstone sequence. This pull-apart transtensional system might explain why low-grade greenstone sequences are preserved and unconformable quartz-rich sedimentary sequences are present in the Cleaverville area.

6.3 Strike-slip pull-apart basin formation

There are two age groups of detrital zircons (3270 Ma and 3020 Ma) in the Forty-Four Hill Member. However, the Sixty-Six Hill Member does not contain the 3270 Ma and 3020 Ma age groups. We interpret that the older zircon age group from the Forty-Four Hill Member (3300–3270 Ma) was sourced from the Karratha Granitoid and that the younger group of zircons (3020 Ma) was derived from southern granitoids (e.g., Harding subcomplex: Kiyokawa et al., 2002; Orpheus Supersuite monzogranite: Hickman & Van Kranendonk, 2012) and from quartz porphyry intrusions in the Nickol Well subcomplex (Kiyokawa et al., 2002). Therefore, these 3020 and 3270 Ma granitic rocks must have been subaerially exposed near the Forty-Four Hill Member at the time

of deposition. During the sedimentation of the Sixty-Six Hill Member, these rocks were not exposed at the surface. In addition, Nelson (1997) reported an age of (3015 ± 5) Ma for strongly foliated volcanoclastic–sedimentary rocks (some ages of 3270–3250 Ma) from near Wickham (sample number 136899; $20^{\circ}41'17''\text{S}$, $117^{\circ}05'07''\text{E}$). This sample was collected from between chert and iron formation sequences, and we consider it to be correlative with the Forty-Four Hill Member.

The strong D_2 sinistral shear fabric in the entire coastal Pilbara Terrane was related to movement of the Sholl Shear Zone (e.g., Sun & Hickman, 1998; Kiyokawa et al., 2002; Hickman, 2004; Hickman, Huston, Van Kranendonk, & Smithies, 2006). We propose that there were two stages of movement on the Sholl Shear Zone. (1) Stage 1: sinistral movement of up to 200 km that formed the Whim Creek Basin. Previous studies have identified an earlier stage of movement up to 200 Myr before deposition of the Whim Creek Group (Hickman, 2016). (2) Stage 2: late-stage dextral movement at 2920 Ma, which involved <50 km of movement (Sun & Hickman, 1998). The Karratha Granitoid (Prinsep Dome) might have been elongated by the D_2 sinistral deformation.

Around this time, several strike-slip pull-apart basins formed throughout the Pilbara Craton (e.g., Krapez & Barley, 1987; Krapez & Eisenlohr, 1998; Van Kranendonk & Collins, 1998). The Lalla Rookh–Western Shaw structural corridor is a

>150-km-long intracrustal deformation zone in eastern Pilbara, which was deformed by sinistral strike-slip deformation at 2930 Ma (Van Kranendonk, 2008). The Sholl Shear Zone also experienced significant movement from 3070 Ma to 2920 Ma (Smith et al., 1998; Hickman, 2004). As such, the Pilbara Craton was affected by region-wide, sinistral strike-slip deformation and the “Cleaverville pull-apart basins” might have formed at this time.

The formation of the coastal Pilbara Terrane occurred as follows: (1) onset of deposition and formation of an oceanic island arc at 3200–3060 Ma; (2) arc–continent accretion at 3070–3050 Ma; (3) strike-slip faulting and strike-slip pull-apart basin formation during continent stabilization at 3000–2930 Ma; and (4) rigid craton formation at 2930–2800 Ma. It took 100–180 Myr to add this new continental crust to the Pilbara Craton.

7. Conclusions

A detailed geological and zircon dating study of the Cleaverville Formation allows the sedimentation and tectonic history of these rocks to be divided into the following three stages.

1) Formation of the volcanic–sedimentary sequence (Dixon Island and Cleaverville Formations) at ca. 3200–3060 Ma. In particular, the BIF Member of the

443 Cleaverville Formation was deposited from 3114 Ma to 3060 Ma. This depositional age
444 is 40–90 Myr older than that proposed in previous studies and pre-dates the Prinsep
445 Orogeny (3070–3050 Ma). The Cleaverville Formation contains a key banded iron
446 formation, which allows stratigraphic correlation from east to west across the
447 Mesoarchean Pilbara Supergroup. The age of the Cleaverville Formation (3.1 Ga) has
448 implications for previous interpretations of stratigraphy in Pilbara.

449 2) Sedimentation of the Sixty-Six Hill Member, which is in unconformable
450 contact with the Lagoon Pillow Basalt and in fault contact with the Cleaverville
451 Formation. Sedimentation was associated with the formation of the Cleaverville Syncline.
452 This deformation is identified as phase D₁ (accretion and collision), which occurred at
453 3070–3050 Ma. This deformation was thus associated with the regional collision event of
454 the Prinsep Orogeny. At this time, the coastal Pilbara Terrane collided with and began to
455 cratonize the Central Pilbara.

456 3) NE-trending strike-slip faults bounding a strike-slip pull-apart basin created a
457 tidal, shallow-ocean depositional setting above the greenstone section after D₁
458 deformation. The strike-slip faults might have had vertical offsets of 2000–4000 m and
459 most of these sedimentary rocks are now eroded. Sandstones with detrital zircon ages of
460 3020 Ma (similar to the Orpheus Supersuite of the Harding complex; Hickman and Van

461 Kranendonk, 2012) and 3270 Ma (similar to the Karratha Granitoid) in this basin indicate
462 that exhumation and erosion occurred prior to strike-slip deformation in the coastal
463 Pilbara Terrane. We propose that this local strike-slip pull-apart basin system was related
464 to the D₂ deformation that affected the entire Pilbara Craton and generated left-lateral
465 shear related to the Sholl Shear Zone from 3000 Ma to 2930 Ma. This strike-slip
466 deformation was the final cratonization event of the Pilbara Craton and occurred 70–140
467 Myr after the Prinsep Orogeny.

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634

Figure and Table Captions

Figure 1. Geological map of the study area. (a) Location map of the Pilbara Craton. (b) Geological map of the Cleaverville area, coastal Pilbara Terrane (after Kiyokawa & Taira, 1998; Kiyokawa et al., 2006, 2012a). Red stars show the sample locations of new zircon U–Pb ages from this study. CL A is the Cleaverville A area, and CL F is the Cleaverville F area.

Figure 2. Stratigraphic columns of the Dixon Island, Cleaverville, and Lizard Hills Formations (after Kiyokawa & Taira, 1998; Kiyokawa et al., 2012a). Stars indicate samples collected for age dating. The numbers of the stars correspond to the numbers on the geological map (Figure 1). Red stars represent samples of this study.

Figure 3. Outcrop photographs of the Cleaverville area. (a) Overview of zircon U–Pb age data for the silicic volcanoclastic–felsic tuff section of the Black Chert Member in the Cleaverville Formation. The silicic volcanoclastic–felsic tuff bed is 2.5 m thick and occurs in a 7-m-wide channelized depression. The lower part of the bed contains black chert fragments, and the upper part contains finely laminated tuff and grades into a black chert sequence. (b) Close-up of the silicic volcanoclastic–felsic tuff in (a). Zircon grains were extracted from 40 kg samples of fine-grained yellow silicic tuff (matrix of black chert fragments). (c) Black chert and pebble-rich conglomerate in the lower part

of the Sixty-Six Hill Member. (d) Close-up of the granule-sized chert–volcaniclastic rocks in the middle part of the Sixty-Six Hill Member. (e) Bedded black cherts from the middle part of the Sixty-Six Hill Member. (f) Homogeneous, fine- to medium-grained, gray sandstone (wacke) in the upper part of the Sixty-Six Hill Member. Sample 100912-15 was taken from these rocks (Figure 4b). (g) Well-sorted, coarse-grained sandstone from the lower part of the Forty-Four Hill Member, with well-preserved herring-bone cross-stratification. The sandstone channel beds are filled with black chert conglomerate and unconformably overlie the Lagoon Pillow Basalt (Regal Formation). (h) Poorly sorted, pebbly, coarse-grained, red sandstone from the middle part of the Forty-Four Hill Member. Pebbles of white vein quartz and sandstone are found in this unit.

Figure 4. Thin section photomicrographs of dated sandstone samples from the Lizard Hills Formation (left-hand side = plane-polarized light; right-hand side = cross-polarized light). a1: Sample 100912-14 (plane-polarized light). Homogeneous, fine- to medium-grained sandstone from the upper part of the Sixty-Six Hill Member, containing rounded grains of quartz, chert, and plagioclase (Figure. 3f). Each grain is coated by silica. a2: Sample 100912-14 in cross-polarized light. b1: Sample 100912-15 (plane-polarized light). Homogeneous, medium-grained sandstone from the upper part of the Sixty-Six Hill Member, containing rounded grains of quartz, chert, and

plagioclase, and white mica in the matrix. b2: Sample 100912-15 (cross-polarized light). c1: Sample 100912-28c-50 (plane-polarized light). Poorly sorted red sandstone from the middle of the Forty-Four Hill Member. c2: Sample 100912-28c-50 (cross-polarized light).

Figure 5. Schematic model of the formation of the Cleaverville Syncline and sedimentation of the Sixty-Six Hill Member. The top figure shows the original stratigraphy. The south limb (Lagoon Pillow Basalt) was folded and thrust during the early stage of fold development. The fold axis area was the site of sedimentation of the Sixty-Six Hill Member after thrusting. After sedimentation of the Sixty-Six Hill Member, compression continued and a tight fold formed during D₂ deformation.

Figure 6. Detrital zircon U–Pb age data. (a) Wasserburg concordia plot for zircons from the fine-grained matrix of the volcanoclastic rocks (fine-grained silicic tuff matrix containing black chert pebbles) in the Black Shale Member of the Cleaverville Formation (sample C911: Location 3 in Figure 1). (b) Backscattered electron images of zircon grains from sample C911. Red circles indicate sites that were dated. (c) Wasserburg concordia plot for zircons in sandstones from the Sixty-Six Hill Member (samples 100912-14 and 100912-15: Locations 4 and 5 in Figure 1) and the Forty-Four

688 Hill Member (sample 100912-28: Location 6 in Figure 1). (d) Age histograms of the
689 zircon ages from (c).

690 Figure 7. D₂ structural map of the coastal Pilbara Terrane. The estimate of ocean
691 area is based on aeromagnetic images from GSWA (Watt, 1995).

692 Figure 8. Schematic geological history of the Cleaverville area of the coastal
693 Pilbara Terrane.

694 Table 1. U–Pb age data for felsic tuff and sandstone detrital zircons.

Legend

Fortescue Group

Mount Roe Basalt

Fold axis

Unconformity

Bedding (Arrow : Stratigraphic up)

Cleavage

Zircon age dating point

Lizard Hills Formation

Forty-Four Hill Member

Chert-Dolomite submember

Brown-Red Sandstone subm.

Quartz Sandstone submember

Sixty-Six Hill Member

Alenite sandstone

Black/white chert

Chert pebbly conglomerate

Cleaverville Formation

BIF Member

Black Shale Member

Port Robinson Basalt

Dixon Island Formation

Regal Formation

Lagoon Pillow Basalt

Lagoon Member

Rhyolite unit

Point Samson Formation

Nickol Well subcomplex

Karratha supercomplex

Lydia Mine complex

Figure 1 ① Kiyokawa et al. (2002), ② Nelson (1998), ③—⑥ This study

Figure 2

LEGEND

DZ	Detrital zircon		Banded iron formation		Well sorted sandstone (quartz arenite)		Black/white chert
	Age dating point		Black shale		Well sorted pebble conglomerate		Pyroclastics
	Black chert veins		Pillow basalt		Poorly sorted sandstone (wacke)		Dolomite
	Thin quartz vein swarm		Massive basalt		Black/white bedded chert		Altered volcanics
	White felsic tuff		Fe rich bedded chert		Ferruginous laminated chert		Red siltstone
	Yellowish brown komatiite lava		Bacterial mat		Poorly sorted pebbly conglomerate		Poorly sorted red-brown sandstone
	Highly altered komatiite lava		Black chert				Gray siltstone

Figure 4

Figure 5

5: Tight folding

During D_2 deformation

4: Fold axis plane deformed (fault)

3: Sedimentation

3060 Ma volcanics

Sixty-Six Hill Member

Black chert fragments

2: Erosion

1: Fold and thrust

Top to northwest thrust

Cleaverville Syncline

D_1 deformation

Original stratigraphy

north

south

Cleaverville Formation

3114 Ma

Port Robinson Basalt

Dixon Island Formation

3195 Ma

Regal Formation

Figure 7

D₂ structural map of the coastal Pilbara terrane

Figure 8

Sandstone ★ This study Volcaniclastics -felsic tuff ▲ Kiyokawa et al. (2002) Granitoid □ □ □ □ Nelson (1998) Smith et al., (1998) Kiyokawa et al. (2002)

Volcaniclastics -felsic tuff ● This study Volcaniclastics -felsic tuff ● Nelson (1998)

LRWS : Lalla Rookh-Western Shaw structural corridor
DZ : Detrital zircon G.: Group Fm.: Formation

TABLE 1. U–Pb age data of felsic tuff and sandstone detrital zircon

Sample number	U	Th	Th/U	²⁰⁶ Pb _{co}	²⁰⁷ Pb [*] / ²⁰⁶ Pb [*]	²³⁸ U/ ²⁰⁶ Pb [*]	²⁰⁶ Pb [*] / ²³⁸ U	²⁰⁷ Pb [*]			
Discordancy	(ppm)	(ppm)		(%)			age (Ma)	age			
CLA (same rock)											
<u>C91107-01.1</u>	###	60	0.51	0.01	#####	± #####	#####	± #####	3029	± 67	####
C91107-02.1	D ###	348	2.86	0.70	#####	± #####	#####	± #####	1707	± ###	####
<u>C91107-02.2</u>	###	68	0.56	0.01	#####	± #####	#####	± #####	2973	± 65	####
C91107-03.1	D ###	777	2.41	3.70	#####	± #####	#####	± #####	1463	± 30	####
C91107-04.1	D ###	168	1.06	0.45	#####	± #####	#####	± #####	2464	± 53	####
C91113-01.1	###	174	0.89	0.06	#####	± #####	#####	± #####	3074	± 58	####
C91113-02.1	D ###	117	0.89	0.09	#####	± #####	#####	± #####	2925	± 62	####
C91113-03.1	###	39	0.34	0.08	#####	± #####	#####	± #####	3297	± 71	####
<u>C91113-04.1</u>	###	304	1.73	0.06	#####	± #####	#####	± #####	3143	± 62	####
C91114-01.1	D ###	978	2.31	0.55	#####	± #####	#####	± #####	2132	± 37	####
C91114-02.1	###	166	0.70	0.05	#####	± #####	#####	± #####	3491	± ###	####
C91114-03.1	D ###	694	1.66	0.23	#####	± #####	#####	± #####	1678	± 29	####
C91114-04.1	D ###	679	2.30	0.21	#####	± #####	#####	± #####	1979	± 36	####
C91114-05.1	###	54	0.48	0.13	#####	± #####	#####	± #####	3567	± 77	####
C91114-06.1	39	33	0.88	0.14	#####	± #####	#####	± #####	3349	± ###	####
<u>C91114-07.1</u>	90	229	2.64	####	#####	± #####	#####	± #####	3067	± 80	####
C91114-08.1	D ###	299	2.62	0.31	#####	± #####	#####	± #####	2086	± 50	####
<u>C91114-09.1</u>	###	287	1.57	0.07	#####	± #####	#####	± #####	3030	± 63	####
C91114-09.2	D 55	27	0.50	0.00	#####	± #####	#####	± #####	2254	± 81	####
C91114-10.1	D ###	###	####	0.81	#####	± #####	#####	± #####	1391	± 41	####
C91114-11.1	D ###	159	0.68	0.06	#####	± #####	#####	± #####	3249	± 63	####
C91119-01.1	D ###	###	0.95	0.35	#####	± #####	#####	± #####	817	± 14	####
C91119-01.2	D ###	###	1.65	0.26	#####	± #####	#####	± #####	874	± 15	####
C91119-02.1	D ###	35	0.19	0.48	#####	± #####	#####	± #####	2539	± 54	####
C91119-03.1	D ###	365	1.85	0.14	#####	± #####	#####	± #####	2398	± 50	####
C91119-04.1	D ###	317	2.27	0.08	#####	± #####	#####	± #####	2493	± 52	####
C91119-05.1	D ###	329	1.49	1.15	#####	± #####	#####	± #####	2075	± 46	####
C91119-06.1	D ###	554	1.76	0.15	#####	± #####	#####	± #####	2473	± 60	####
C91120-01.1	D 51	64	1.29	0.35	#####	± #####	#####	± #####	2582	± 90	####
<u>C91120-03.1</u>	34	38	1.17	####	#####	± #####	#####	± #####	3020	± ###	####
<u>C91120-04.1</u>	###	49	0.49	0.11	#####	± #####	#####	± #####	3241	± 82	####
C91120-05.1	D ###	297	0.98	0.10	#####	± #####	#####	± #####	2565	± 48	####

<u>C91120-06.1</u>		72	67	0.96	0.05	#####	±	#####	#####	±	#####	3018	± 89	####
<u>C91121-02.1</u>		###	83	0.48	0.03	#####	±	#####	#####	±	#####	3153	± 63	####
C91121-03.1	D	###	874	1.63	0.29	#####	±	#####	#####	±	#####	1479	± 32	####
<u>C91121-04.1</u>		###	79	0.44	0.00	#####	±	#####	#####	±	#####	3160	± 62	####
C91121-05.1	D	###	100	0.55	0.07	#####	±	#####	#####	±	#####	2808	± 54	####
C91121-06.1	D	###	430	2.14	0.17	#####	±	#####	#####	±	#####	2257	± 44	####
C91123-01.1	D	###	374	1.16	0.67	#####	±	#####	#####	±	#####	2385	± 41	####
C91123-02.1	D	###	###	2.49	0.22	#####	±	#####	#####	±	#####	1661	± 29	####
C91123-03.1	D	###	###	3.34	0.31	#####	±	#####	#####	±	#####	1693	± 28	####
C91126-01.1	D	53	49	0.97	####	#####	±	#####	#####	±	#####	3358	± ###	####
C91126-02.1	D	###	###	2.99	0.30	#####	±	#####	#####	±	#####	1945	± 34	####
C91127-01.1	D	###	256	0.98	0.77	#####	±	#####	#####	±	#####	2904	± 53	####
C91127-02.1	D	###	595	0.93	2.58	#####	±	#####	#####	±	#####	877	± 16	####
<u>C91127-03.1</u>		###	155	0.76	0.01	#####	±	#####	#####	±	#####	3037	± 58	####

Forty-Four Hill	U	Th	Th/U	²⁰⁶ Pb _{co}	²⁰⁷ Pb [*] / ²⁰⁶ Pb [*]	²³⁸ U/ ²⁰⁶ Pb [*]	²⁰⁶ Pb [*] / ²³⁸ U	²⁰⁷ Pb [*]
100912-28	(ppm)	(ppm)		(%)			age (Ma)	age
C91228-01.1	D ###	110	0.24	3.31	##### ± #####	##### ± #####	1606 ± 20	####
C91228-02.1	55	47	0.89	0.10	##### ± #####	##### ± #####	3181 ± 57	####
C91228-03.1	D ###	736	0.76	3.37	##### ± #####	##### ± #####	1012 ± 12	####
C91228-04.1	D ###	116	0.32	2.03	##### ± #####	##### ± #####	1860 ± 23	####
C91228-05.1	D ###	978	1.54	3.93	##### ± #####	##### ± #####	1105 ± 14	####
C91228-06.1	###	30	0.26	0.00	##### ± #####	##### ± #####	3009 ± 43	####
C91228-07.1	###	27	0.12	0.07	##### ± #####	##### ± #####	2862 ± 36	####
C91228-08.1	###	164	0.69	0.06	##### ± #####	##### ± #####	3137 ± 38	####
C91228-09.1	D ###	194	0.49	2.52	##### ± #####	##### ± #####	1621 ± 20	####
C91228-10.1	D ###	268	1.20	2.26	##### ± #####	##### ± #####	2047 ± 27	####
C91228-11.1	D ###	269	0.81	1.20	##### ± #####	##### ± #####	2079 ± 25	####
C91228-12.1	###	85	0.52	0.07	##### ± #####	##### ± #####	2951 ± 39	####
C91228-13.1	###	36	0.23	0.01	##### ± #####	##### ± #####	2939 ± 39	####
C91228-14.1	D ###	591	1.29	2.81	##### ± #####	##### ± #####	1596 ± 21	####
C91228-15.1	###	51	0.31	0.03	##### ± #####	##### ± #####	3014 ± 40	####
C91228-17.1	###	26	0.26	0.10	##### ± #####	##### ± #####	2951 ± 44	####
C91228-18.1	###	144	0.68	0.03	##### ± #####	##### ± #####	3259 ± 40	####
C91228-16.1	D ###	130	0.37	1.82	##### ± #####	##### ± #####	2016 ± 25	####
C91228-19.1	D ###	###	2.55	2.22	##### ± #####	##### ± #####	1675 ± 20	####

C91228-20.1	D	###	237	0.53	2.26	#####	±	#####	#####	±	#####	1728	± 21	####
C91228-21.1		69	76	1.13	0.10	#####	±	#####	#####	±	#####	3208	± 52	####
C91228-22.1	D	###	137	0.46	2.01	#####	±	#####	#####	±	#####	1684	± 21	####
C91228-23.1	D	###	649	0.99	3.19	#####	±	#####	#####	±	#####	997	± 13	####
C91228-24.1	D	###	116	0.42	0.40	#####	±	#####	#####	±	#####	2717	± 33	####
C91228-25.1	D	###	175	1.04	0.29	#####	±	#####	#####	±	#####	3142	± 41	####
C91228-26.1	D	###	193	0.94	0.14	#####	±	#####	#####	±	#####	2718	± 35	####
C91228-27.1	D	###	65	0.23	0.23	#####	±	#####	#####	±	#####	2697	± 36	####
C91228-28.1	D	###	339	0.54	2.39	#####	±	#####	#####	±	#####	1372	± 17	####
C91228-29.1		82	102	1.29	0.11	#####	±	#####	#####	±	#####	3198	± 51	####
C91228-30.1	D	###	952	0.91	5.45	#####	±	#####	#####	±	#####	927	± 12	####
C91228-31.1		###	140	1.32	0.03	#####	±	#####	#####	±	#####	3199	± 49	####
C91228-32.1		###	42	0.28	0.03	#####	±	#####	#####	±	#####	2926	± 42	####
C91228-33.1	D	###	104	0.43	0.67	#####	±	#####	#####	±	#####	2407	± 30	####
C91228-34.1	D	###	###	1.77	4.52	#####	±	#####	#####	±	#####	1074	± 14	####
C91228-35.1	D	###	115	0.30	1.81	#####	±	#####	#####	±	#####	1724	± 58	####
C91228-36.1	D	###	121	0.62	0.34	#####	±	#####	#####	±	#####	2021	± 27	####
C91228-37.1		###	59	0.50	0.02	#####	±	#####	#####	±	#####	3046	± 42	####
C91228-37.2	D	###	78	0.70	0.41	#####	±	#####	#####	±	#####	2681	± 40	####
C91228-38.1	D	###	792	1.32	2.85	#####	±	#####	#####	±	#####	1152	± 15	####
C91228-39.1		###	66	0.43	0.08	#####	±	#####	#####	±	#####	3183	± 44	####
C91228-40.1		56	45	0.82	0.20	#####	±	#####	#####	±	#####	3113	± 57	####
C91228-41.1	D	###	282	0.48	3.10	#####	±	#####	#####	±	#####	1428	± 18	####
C91228-42.1		###	58	0.26	0.20	#####	±	#####	#####	±	#####	2934	± 37	####
C91228-43.1	D	###	148	0.58	0.99	#####	±	#####	#####	±	#####	2248	± 29	####
C91228-44.1		###	176	0.67	0.19	#####	±	#####	#####	±	#####	2874	± 36	####
C91228-44.2		###	135	0.64	0.01	#####	±	#####	#####	±	#####	2992	± 40	####
C91228-45.1		###	41	0.30	0.01	#####	±	#####	#####	±	#####	2904	± 42	####
C91228-45.2	D	###	79	0.37	1.09	#####	±	#####	#####	±	#####	2052	± 29	####
C91228-46.1	D	###	112	0.42	0.62	#####	±	#####	#####	±	#####	2236	± 29	####
C91228-47.1	D	###	65	0.42	0.16	#####	±	#####	#####	±	#####	2726	± 41	####
C91228-48.1	D	###	264	0.99	1.27	#####	±	#####	#####	±	#####	2069	± 27	####
C91228-48.2	D	###	133	0.48	0.61	#####	±	#####	#####	±	#####	2359	± 30	####
C91228-49.1	D	###	128	0.53	0.54	#####	±	#####	#####	±	#####	2625	± 34	####
C91228-50.1	D	###	423	0.83	2.47	#####	±	#####	#####	±	#####	1742	± 21	####
C91228-51.1	D	###	172	0.34	2.43	#####	±	#####	#####	±	#####	1549	± 19	####

C91228-52.1	D	###	80	0.29	0.33	#####	±	#####	#####	±	#####	2753	± 35	####
C91228-53.1	D	###	276	0.64	1.38	#####	±	#####	#####	±	#####	1918	± 28	####
C91228-55.1	D	###	194	0.40	2.06	#####	±	#####	#####	±	#####	1819	± 23	####
C91228-56.1	D	###	55	0.26	0.52	#####	±	#####	#####	±	#####	2707	± 37	####
C91228-57.1	D	###	245	0.59	2.33	#####	±	#####	#####	±	#####	1917	± 24	####
C91228-58.1		###	39	0.33	0.46	#####	±	#####	#####	±	#####	2858	± 44	####
C91228-59.1		###	37	0.27	0.02	#####	±	#####	#####	±	#####	2952	± 44	####
C91228-60.1		###	41	0.37	0.02	#####	±	#####	#####	±	#####	2938	± 46	####
C91228-61.1	D	###	144	0.44	1.75	#####	±	#####	#####	±	#####	2210	± 28	####

Sixty-Six Hill M	U	Th	Th/U	²⁰⁶ Pb _{co}	²⁰⁷ Pb [*] / ²⁰⁶ Pb [*]	²³⁸ U/ ²⁰⁶ Pb [*]	²⁰⁶ Pb [*] / ²³⁸ U	²⁰⁷ Pb [*]
100912-14	(ppm)	(ppm)		(%)			age (Ma)	age
C91214-01.1	###	512	1.71	0.57	##### ± #####	##### ± #####	2852 ± 31	####
C91214-01.2	###	108	0.47	0.04	##### ± #####	##### ± #####	3108 ± 34	####
C91214-02.1	94	60	0.66	0.10	##### ± #####	##### ± #####	3079 ± 47	####
C91214-03.1	83	56	0.70	0.04	##### ± #####	##### ± #####	3144 ± 41	####
C91214-04.1	###	158	0.64	0.04	##### ± #####	##### ± #####	3078 ± 34	####
C91214-05.1	90	48	0.55	0.14	##### ± #####	##### ± #####	3166 ± 42	####
C91214-06.1	95	62	0.67	0.19	##### ± #####	##### ± #####	3116 ± 39	####
C91214-07.1	###	115	0.98	0.10	##### ± #####	##### ± #####	3054 ± 37	####
C91214-08.1	###	75	0.68	—	##### ± #####	##### ± #####	3119 ± 39	####
C91214-09.1	###	144	0.57	0.07	##### ± #####	##### ± #####	3069 ± 34	####
C91214-10.1	###	238	0.82	0.19	##### ± #####	##### ± #####	2994 ± 32	####
C91214-11.1	###	169	1.30	0.10	##### ± #####	##### ± #####	3130 ± 39	####
C91214-12.1	###	115	0.59	0.24	##### ± #####	##### ± #####	3018 ± 34	####
C91214-13.1	###	167	0.63	0.18	##### ± #####	##### ± #####	3011 ± 37	####
C91214-14.1	###	93	0.40	0.10	##### ± #####	##### ± #####	3081 ± 41	####
C91214-15.1	###	101	0.69	5.00	##### ± #####	##### ± #####	2923 ± 42	####
C91214-16.1	###	47	0.22	0.08	##### ± #####	##### ± #####	3141 ± 44	####
C91214-17.1	99	69	0.72	0.16	##### ± #####	##### ± #####	3028 ± 68	####
C91214-18.1	###	365	1.05	0.28	##### ± #####	##### ± #####	3049 ± 33	####
C91214-19.1	###	91	0.48	0.05	##### ± #####	##### ± #####	3085 ± 36	####
C91214-20.1	99	76	0.79	0.12	##### ± #####	##### ± #####	3495 ± 44	####
C91214-21.1	95	56	0.61	0.26	##### ± #####	##### ± #####	3216 ± 44	####
C91214-22.1	###	140	1.09	—	##### ± #####	##### ± #####	3149 ± 39	####
C91214-23.1	###	155	0.60	0.04	##### ± #####	##### ± #####	3104 ± 34	####

C91214-24.1	###	71	0.58	—	#####	±	#####	#####	±	#####	3257	± 40	####
C91214-25.1	###	144	0.55	0.05	#####	±	#####	#####	±	#####	3097	± 34	####
C91214-26.1	###	190	1.24	0.27	#####	±	#####	#####	±	#####	2932	± 36	####
C91214-27.1	###	211	1.13	0.12	#####	±	#####	#####	±	#####	3268	± 43	####
C91214-28.1	69	37	0.55	0.27	#####	±	#####	#####	±	#####	3122	± 47	####
C91214-29.1	55	17	0.35	—	#####	±	#####	#####	±	#####	3076	± 58	####
C91214-30.1	95	57	0.63	0.12	#####	±	#####	#####	±	#####	3150	± 44	####
C91214-31.1	72	37	0.54	0.01	#####	±	#####	#####	±	#####	3107	± 55	####
C91214-32.1	###	102	0.78	0.09	#####	±	#####	#####	±	#####	3121	± 39	####
C91214-33.1	61	33	0.56	0.20	#####	±	#####	#####	±	#####	3163	± 48	####
C91214-34.1	###	103	0.44	0.02	#####	±	#####	#####	±	#####	3106	± 35	####
C91214-35.1	###	246	0.84	0.12	#####	±	#####	#####	±	#####	3009	± 35	####
C91214-36.1	###	126	0.96	0.07	#####	±	#####	#####	±	#####	3048	± 38	####
C91214-37.1	###	124	0.77	0.04	#####	±	#####	#####	±	#####	3102	± 36	####
C91214-38.1	###	78	0.76	0.13	#####	±	#####	#####	±	#####	3068	± 39	####
C91214-39.1	###	209	0.67	0.05	#####	±	#####	#####	±	#####	3082	± 33	####
C91214-40.1	###	128	0.53	—	#####	±	#####	#####	±	#####	3004	± 33	####
C91214-41.1	###	150	0.63	0.00	#####	±	#####	#####	±	#####	3731	± 40	####
C91214-42.1	30	20	0.67	0.41	#####	±	#####	#####	±	#####	3091	± 57	####
C91214-43.1	94	54	0.60	0.08	#####	±	#####	#####	±	#####	3053	± 51	####
C91214-44.1	###	180	0.75	0.07	#####	±	#####	#####	±	#####	3096	± 39	####
C91214-45.1	###	157	0.64	0.04	#####	±	#####	#####	±	#####	3098	± 34	####
C91214-46.1	87	55	0.65	0.06	#####	±	#####	#####	±	#####	3207	± 42	####
C91214-47.1	84	42	0.51	0.17	#####	±	#####	#####	±	#####	3113	± 42	####
C91214-48.1	###	122	0.54	0.02	#####	±	#####	#####	±	#####	3137	± 35	####
C91214-49.1	###	198	0.79	0.03	#####	±	#####	#####	±	#####	3171	± 35	####
C91214-50.1	98	51	0.54	0.07	#####	±	#####	#####	±	#####	3111	± 40	####
C91214-51.1	###	137	0.71	—	#####	±	#####	#####	±	#####	3280	± 37	####
C91214-52.1	###	103	0.52	0.08	#####	±	#####	#####	±	#####	3049	± 39	####
C91214-53.1	###	237	0.72	0.01	#####	±	#####	#####	±	#####	3084	± 33	####
C91214-54.1	###	133	0.65	0.02	#####	±	#####	#####	±	#####	3045	± 34	####
C91214-55.1	###	60	0.54	0.07	#####	±	#####	#####	±	#####	3132	± 39	####
C91214-56.1	###	202	0.80	0.05	#####	±	#####	#####	±	#####	3065	± 34	####
C91214-57.1	###	116	0.54	0.00	#####	±	#####	#####	±	#####	3166	± 35	####
C91214-58.1	###	188	0.68	0.06	#####	±	#####	#####	±	#####	3080	± 33	####
C91214-59.1	###	141	0.55	0.03	#####	±	#####	#####	±	#####	3177	± 35	####

C91214-60.1	###	98	0.83	0.01	#####	±	#####	#####	±	#####	3089	± 38	####
C91214-61.1	###	18	0.19	0.03	#####	±	#####	#####	±	#####	3462	± 44	####
C91214-62.1	###	153	0.90	0.04	#####	±	#####	#####	±	#####	3100	± 36	####
C91214-63.1	###	123	0.63	0.07	#####	±	#####	#####	±	#####	3116	± 35	####
C91214-64.1	###	93	0.74	0.05	#####	±	#####	#####	±	#####	3066	± 43	####
C91214-65.1	###	94	0.62	0.09	#####	±	#####	#####	±	#####	3310	± 39	####
C91214-66.1	###	78	0.44	0.06	#####	±	#####	#####	±	#####	3089	± 42	####
C91214-67.1	###	104	0.68	—	#####	±	#####	#####	±	#####	3094	± 37	####
C91214-68.1	###	146	0.54	—	#####	±	#####	#####	±	#####	3116	± 34	####
C91214-69.1	###	111	0.57	0.25	#####	±	#####	#####	±	#####	3014	± 34	####
C91214-70.1	###	60	0.63	0.09	#####	±	#####	#####	±	#####	3188	± 49	####
C91214-71.1	###	70	0.54	0.12	#####	±	#####	#####	±	#####	3028	± 37	####
C91214-72.1	###	103	0.47	0.01	#####	±	#####	#####	±	#####	3096	± 34	####
C91214-73.1	85	53	0.64	0.10	#####	±	#####	#####	±	#####	3181	± 42	####
C91214-74.1	###	201	0.73	0.06	#####	±	#####	#####	±	#####	3303	± 35	####
C91214-75.1	97	56	0.59	—	#####	±	#####	#####	±	#####	3133	± 42	####
C91214-76.1	###	136	0.56	0.06	#####	±	#####	#####	±	#####	2979	± 32	####
C91214-77.1	71	43	0.63	0.10	#####	±	#####	#####	±	#####	3080	± 43	####
C91214-78.1	###	137	0.78	0.10	#####	±	#####	#####	±	#####	3050	± 35	####
C91214-79.1	###	174	0.61	0.04	#####	±	#####	#####	±	#####	3104	± 34	####
C91214-80.1	###	251	0.99	0.05	#####	±	#####	#####	±	#####	3424	± 37	####
C91214-81.1	90	45	0.52	—	#####	±	#####	#####	±	#####	3050	± 41	####
C91214-82.1	74	53	0.74	0.10	#####	±	#####	#####	±	#####	3183	± 47	####
C91214-83.1	###	259	0.72	0.06	#####	±	#####	#####	±	#####	3050	± 37	####
C91214-84.1	###	135	0.69	0.02	#####	±	#####	#####	±	#####	3324	± 38	####
C91214-85.1	###	279	0.80	0.06	#####	±	#####	#####	±	#####	3050	± 33	####
C91214-86.1	###	104	0.70	0.08	#####	±	#####	#####	±	#####	3074	± 37	####
C91214-87.1	76	41	0.56	0.12	#####	±	#####	#####	±	#####	3062	± 43	####
C91214-88.1	###	177	0.57	0.11	#####	±	#####	#####	±	#####	3019	± 35	####

Sixty-Six Hill M	U	Th	Th/U	²⁰⁶ Pb _{co}	²⁰⁷ Pb [*] / ²⁰⁶ Pb [*]	²³⁸ U/ ²⁰⁶ Pb [*]	²⁰⁶ Pb [*] / ²³⁸ U	²⁰⁷ Pb [*]
100912-15	(ppm)	(ppm)		(%)			age (Ma)	age
C91215-2.1	###	206	1.05	0.16	#####	±	#####	2235 ± 24
C91215-26.1	70	57	0.85	0.03	#####	±	#####	3055 ± 35

C91215-8.1	13	9	0.69	0.42	#####	±	#####	#####	±	#####	3176	± 77	####
C91215-60.1	D ###	285	0.52	2.08	#####	±	#####	#####	±	#####	1669	± 11	####
C91215-85.1	###	116	0.59	0.01	#####	±	#####	#####	±	#####	3102	± 23	####
C91215-161.1	###	141	1.15	0.01	#####	±	#####	#####	±	#####	3319	± 30	####
C91215-314.1	###	67	0.58	—	#####	±	#####	#####	±	#####	3156	± 29	####
C91215-286.1	###	134	1.01	0.03	#####	±	#####	#####	±	#####	3267	± 28	####
C91215-320.1	###	115	0.52	0.01	#####	±	#####	#####	±	#####	3047	± 22	####
C91215-328.1	###	130	0.76	0.02	#####	±	#####	#####	±	#####	3097	± 25	####
C91215-156.1	39	16	0.43	0.15	#####	±	#####	#####	±	#####	2977	± 44	####
C91215-59.1	###	99	0.71	0.04	#####	±	#####	#####	±	#####	3227	± 28	####
C91215-410.1	81	47	0.61	0.06	#####	±	#####	#####	±	#####	3085	± 33	####
C91215-110.1	###	126	0.50	0.02	#####	±	#####	#####	±	#####	3037	± 21	####
C91215-80.1	74	40	0.56	0.11	#####	±	#####	#####	±	#####	3051	± 35	####
C91215-381.1	###	68	0.46	0.01	#####	±	#####	#####	±	#####	3068	± 26	####
C91215-453.1	93	78	0.86	0.03	#####	±	#####	#####	±	#####	3077	± 32	####
C91215-425.1	###	68	0.49	0.06	#####	±	#####	#####	±	#####	3010	± 26	####
C91215-480.1	40	17	0.43	0.17	#####	±	#####	#####	±	#####	3058	± 45	####
C91215-509.1	###	121	0.59	—	#####	±	#####	#####	±	#####	3121	± 23	####
C91215-436.1	###	90	0.53	—	#####	±	#####	#####	±	#####	3262	± 26	####
C91215-437.1	###	57	0.51	0.02	#####	±	#####	#####	±	#####	3488	± 32	####
C91215-438.1	95	52	0.57	0.02	#####	±	#####	#####	±	#####	3121	± 32	####
C91215-392.1	###	62	0.44	0.10	#####	±	#####	#####	±	#####	3104	± 27	####
C91215-414.1	15	10	0.68	—	#####	±	#####	#####	±	#####	3228	± 76	####
C91215-470.1	29	46	1.62	0.03	#####	±	#####	#####	±	#####	3319	± 57	####
C91215-349.1	###	140	0.60	0.02	#####	±	#####	#####	±	#####	3085	± 22	####
C91215-63.1	30	14	0.46	—	#####	±	#####	#####	±	#####	3163	± 55	####
C91215-86.1	###	73	0.62	0.04	#####	±	#####	#####	±	#####	3117	± 29	####
C91215-212.1	###	85	0.85	—	#####	±	#####	#####	±	#####	3123	± 31	####
C91215-211.1	###	200	0.96	0.03	#####	±	#####	#####	±	#####	3186	± 24	####
C91215-209.1	###	144	0.69	0.00	#####	±	#####	#####	±	#####	3442	± 25	####
C91215-165.1	###	162	0.62	0.00	#####	±	#####	#####	±	#####	3067	± 21	####
C91215-166.1	###	68	0.63	—	#####	±	#####	#####	±	#####	3103	± 29	####
C91215-119.1	###	100	0.57	—	#####	±	#####	#####	±	#####	3097	± 24	####
C91215-87.1	###	155	0.43	0.07	#####	±	#####	#####	±	#####	3097	± 19	####
C91215-48.1	###	130	0.50	0.01	#####	±	#####	#####	±	#####	3052	± 20	####
C91215-377.1	###	136	0.46	0.00	#####	±	#####	#####	±	#####	3063	± 20	####

C91215-356.1	91	51	0.58	—	#####	±	#####	#####	±	#####	3152	± 33	####
C91215-355.1	###	98	0.74	0.06	#####	±	#####	#####	±	#####	3101	± 27	####
C91215-357.1	###	53	0.52	0.05	#####	±	#####	#####	±	#####	3100	± 30	####
C91215-427.1	56	34	0.62	0.02	#####	±	#####	#####	±	#####	3030	± 39	####
C91215-454.1	###	94	0.64	—	#####	±	#####	#####	±	#####	3115	± 26	####
C91215-426.1	###	159	0.68	—	#####	±	#####	#####	±	#####	3073	± 22	####
C91215-468.1	###	132	0.82	—	#####	±	#####	#####	±	#####	3078	± 25	####
C91215-500.1	###	208	0.75	0.04	#####	±	#####	#####	±	#####	3248	± 21	####
C91215-444.1	67	38	0.58	0.06	#####	±	#####	#####	±	#####	3099	± 36	####
C91215-445.1	###	129	0.52	—	#####	±	#####	#####	±	#####	3174	± 22	####
C91215-177.1	###	97	0.48	0.00	#####	±	#####	#####	±	#####	3109	± 23	####
C91215-252.1	###	72	0.63	0.05	#####	±	#####	#####	±	#####	3084	± 28	####
C91215-95.1	###	207	0.99	0.09	#####	±	#####	#####	±	#####	2947	± 21	####
C91215-352.1	###	156	0.66	—	#####	±	#####	#####	±	#####	3063	± 21	####
C91215-200.1	###	78	0.69	—	#####	±	#####	#####	±	#####	3146	± 29	####
C91215-204.1	###	65	0.62	—	#####	±	#####	#####	±	#####	3055	± 28	####
C91215-247.1	###	118	0.49	0.04	#####	±	#####	#####	±	#####	3073	± 21	####
C91215-215.1	###	60	0.61	0.06	#####	±	#####	#####	±	#####	3134	± 29	####
C91215-270.1 D	###	###	4.05	2.77	#####	±	#####	#####	±	#####	1832	± 11	####
C91215-55.1 D	###	350	1.36	0.69	#####	±	#####	#####	±	#####	2474	± 17	####
C91215-366.1	23	14	0.66	—	#####	±	#####	#####	±	#####	3155	± 58	####
C91215-523.1	63	34	0.56	—	#####	±	#####	#####	±	#####	3112	± 37	####
C91215-50.1	###	95	0.55	0.02	#####	±	#####	#####	±	#####	3577	± 26	####
C91215-280.1	###	117	0.63	0.06	#####	±	#####	#####	±	#####	3089	± 23	####
C91215-281.1	76	45	0.61	0.05	#####	±	#####	#####	±	#####	3114	± 33	####
C91215-106.1 D	###	607	1.17	3.34	#####	±	#####	#####	±	#####	1515	± 9	####
C91215-107.1	91	60	0.68	0.14	#####	±	#####	#####	±	#####	3026	± 30	####
C91215-73.1	###	73	0.55	0.06	#####	±	#####	#####	±	#####	3069	± 26	####
C91215-74.1	84	62	0.76	0.05	#####	±	#####	#####	±	#####	3099	± 32	####
C91215-39.1	###	60	0.49	0.03	#####	±	#####	#####	±	#####	3067	± 27	####
C91215-81.1	###	218	1.60	0.02	#####	±	#####	#####	±	#####	3371	± 28	####
C91215-502.1	###	160	0.55	0.05	#####	±	#####	#####	±	#####	3159	± 20	####
C91215-471.1	###	76	0.76	0.04	#####	±	#####	#####	±	#####	3096	± 30	####
C91215-416.1	###	109	0.67	—	#####	±	#####	#####	±	#####	3161	± 26	####
C91215-304.1	###	82	0.76	—	#####	±	#####	#####	±	#####	3040	± 29	####
C91215-534.1	###	113	0.52	—	#####	±	#####	#####	±	#####	3125	± 22	####

C91215-486.1	91	51	0.58	—	#####	± #####	#####	± #####	3097	± 31	####
C91215-476.1	###	75	0.65	0.01	#####	± #####	#####	± #####	3283	± 29	####
C91215-478.1	71	44	0.64	0.05	#####	± #####	#####	± #####	3163	± 35	####
C91215-560.1 D	###	###	2.03	3.11	#####	± #####	#####	± #####	1199	± 7	####
C91215-541.1	###	63	0.58	0.07	#####	± #####	#####	± #####	3034	± 29	####
C91215-562.1	90	70	0.80	0.08	#####	± #####	#####	± #####	3099	± 31	####
C91215-517.1	###	146	0.72	0.01	#####	± #####	#####	± #####	3254	± 24	####
C91215-277.1	###	142	0.62	—	#####	± #####	#####	± #####	3094	± 22	####
C91215-275.1	68	35	0.53	0.03	#####	± #####	#####	± #####	3135	± 36	####
C91215-323.1	###	119	1.09	0.05	#####	± #####	#####	± #####	3085	± 29	####
C91215-451.1	###	143	1.06	—	#####	± #####	#####	± #####	3086	± 27	####
C91215-372.1	72	38	0.55	0.01	#####	± #####	#####	± #####	3127	± 35	####
C91215-102.1	56	34	0.62	0.03	#####	± #####	#####	± #####	3085	± 38	####
C91215-5.1	###	141	0.53	0.02	#####	± #####	#####	± #####	3108	± 20	####
C91215-103.1	96	62	0.67	0.03	#####	± #####	#####	± #####	3185	± 32	####
C91215-279.1	90	37	0.43	0.06	#####	± #####	#####	± #####	3073	± 30	####
C91215-367.1	81	44	0.56	—	#####	± #####	#####	± #####	3049	± 32	####
C91215-389.1	86	52	0.62	0.03	#####	± #####	#####	± #####	3110	± 32	####
C91215-390.1	80	51	0.66	0.06	#####	± #####	#####	± #####	3117	± 33	####
C91215-369.1	###	136	0.60	—	#####	± #####	#####	± #####	3101	± 21	####
C91215-370.1	###	114	0.83	0.01	#####	± #####	#####	± #####	3086	± 25	####
C91215-375.1	###	121	0.91	—	#####	± #####	#####	± #####	3074	± 26	####
C91215-345.1	###	124	0.56	0.00	#####	± #####	#####	± #####	3120	± 21	####
C91215-346.1	60	36	0.62	0.09	#####	± #####	#####	± #####	3102	± 37	####
C91215-4.1 D	###	###	4.69	4.13	#####	± #####	#####	± #####	1940	± 12	####
C91215-71.1	###	144	0.93	0.01	#####	± #####	#####	± #####	3091	± 24	####
C91215-140.1	47	28	0.61	0.04	#####	± #####	#####	± #####	3127	± 41	####
C91215-250.1	###	213	0.66	0.07	#####	± #####	#####	± #####	2993	± 18	####
C91215-251.1	###	178	1.19	0.07	#####	± #####	#####	± #####	3270	± 26	####
C91215-373.1	97	63	0.67	0.04	#####	± #####	#####	± #####	3110	± 29	####
C91215-388.1	###	122	0.50	0.02	#####	± #####	#####	± #####	3122	± 21	####
C91215-104.1	###	146	0.83	0.03	#####	± #####	#####	± #####	3111	± 23	####

Isotopic ratios are given with 1 σ uncertainties, after the correction for common Pb using the ²⁰⁴Pb correction. Disc. (%) denotes the percentage of discordancy (e.g. Song et al., 1996). D: discordant

$^{206}\text{Pb}^*$	Disc.
(Ma)	(%)

$\pm 13 \quad 4$

$\pm 43 \quad 50$

$\pm 13 \quad 6$

$\pm 40 \quad 56$

$\pm 25 \quad 24$

$\pm 10 \quad 9$

$\pm 19 \quad 13$

$\pm 12 \quad 5$

$\pm 11 \quad 0$

$\pm 10 \quad 42$

$\pm 17 \quad -2$

$\pm 10 \quad 57$

$\pm 9 \quad 50$

$\pm 21 \quad 5$

$\pm 25 \quad -3$

$\pm 16 \quad 2$

$\pm 16 \quad 38$

$\pm 12 \quad 7$

$\pm 26 \quad 31$

$\pm 26 \quad 60$

$\pm 12 \quad 23$

$\pm 11 \quad 77$

$\pm 11 \quad 75$

$\pm 17 \quad 21$

$\pm 13 \quad 26$

$\pm 11 \quad 34$

$\pm 15 \quad 38$

$\pm 5 \quad 25$

$\pm 26 \quad 21$

$\pm 26 \quad 5$

$\pm 16 \quad -7$

$\pm 10 \quad 21$

± 19	3
± 12	-3
± 10	57
± 12	-2
± 11	12
± 12	32
± 12	23
± 11	51
± 10	51
± 18	9
± 12	43
± 10	16
± 30	73
± 10	1

²⁰⁶Pb* Disc.

<u>(Ma)</u>	<u>(%)</u>
± 10	53
± 9	3
± 13	67
± 10	44
± 14	67
± 7	1
± 5	6
± 20	3
± 10	52
± 23	44
± 7	40
± 6	3
± 6	3
± 30	55
± 6	0
± 8	2
± 5	-2
± 9	38
± 9	42

± 9 50
 ± 8 0
 ± 10 50
 ± 13 70
 ± 6 12
 ± 18 14
 ± 5 21
 ± 8 14
 ± 8 62
 ± 8 3
 ± 18 67
 ± 7 2
 ± 7 3
 ± 8 25
 ± 17 69
 ± 36 47
 ± 8 38
 ± 7 9
 ± 9 21
 ± 12 67
 ± 6 3
 ± 11 6
 ± 12 57
 ± 6 3
 ± 9 30
 ± 6 6
 ± 6 1
 ± 7 5
 ± 10 37
 ± 9 29
 ± 8 12
 ± 10 34
 ± 7 25
 ± 8 16
 ± 10 45
 ± 9 56

± 6	11
± 11	48
± 10	44
± 8	13
± 9	47
± 10	6
± 7	2
± 8	4
± 9	32

$^{206}\text{Pb}^*$	Disc.
(Ma)	(%)

± 9	9
± 7	-1
± 12	0
± 13	-2
± 7	1
± 13	-3
± 12	0
± 10	1
± 11	-1
± 7	0
± 7	3
± 13	4
± 9	2
± 7	2
± 11	1
± 42	6
± 10	-2
± 13	2
± 7	1
± 9	0
± 10	-2
± 14	-5
± 11	-3
± 8	0

$\pm 12 \quad 0$
 $\pm 8 \quad 0$
 $\pm 11 \quad 6$
 $\pm 9 \quad -2$
 $\pm 19 \quad 0$
 $\pm 52 \quad 2$
 $\pm 17 \quad -3$
 $\pm 31 \quad -1$
 $\pm 11 \quad -1$
 $\pm 16 \quad -2$
 $\pm 10 \quad 0$
 $\pm 9 \quad 3$
 $\pm 11 \quad 1$
 $\pm 9 \quad 0$
 $\pm 12 \quad 1$
 $\pm 7 \quad 0$
 $\pm 8 \quad 3$
 $\pm 6 \quad 2$
 $\pm 23 \quad 0$
 $\pm 13 \quad 1$
 $\pm 8 \quad 0$
 $\pm 8 \quad 0$
 $\pm 12 \quad 1$
 $\pm 14 \quad -1$
 $\pm 8 \quad -1$
 $\pm 7 \quad -3$
 $\pm 12 \quad -1$
 $\pm 8 \quad -1$
 $\pm 9 \quad 1$
 $\pm 7 \quad 0$
 $\pm 8 \quad 2$
 $\pm 11 \quad -1$
 $\pm 7 \quad 1$
 $\pm 8 \quad -3$
 $\pm 7 \quad 0$
 $\pm 7 \quad -3$

± 11	1
± 11	-4
± 12	0
± 9	-1
± 11	2
± 9	-3
± 9	0
± 9	0
± 7	-1
± 9	2
± 12	-3
± 10	2
± 8	0
± 13	-2
± 6	1
± 12	-2
± 8	4
± 14	0
± 9	1
± 8	-1
± 7	0
± 13	2
± 17	-4
± 7	2
± 8	0
± 7	1
± 10	1
± 15	0
± 8	3

$/^{206}\text{Pb}^*$ Disc.

(Ma)	(%)
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± 6	5
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± 11	2
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$\pm 27 \quad -5$
 $\pm 7 \quad 53$
 $\pm 6 \quad 2$
 $\pm 7 \quad -1$
 $\pm 8 \quad -3$
 $\pm 7 \quad 0$
 $\pm 6 \quad 2$
 $\pm 7 \quad 0$
 $\pm 15 \quad 4$
 $\pm 7 \quad 0$
 $\pm 10 \quad -1$
 $\pm 6 \quad 2$
 $\pm 11 \quad 2$
 $\pm 43 \quad 1$
 $\pm 9 \quad 0$
 $\pm 8 \quad 4$
 $\pm 15 \quad 0$
 $\pm 6 \quad -1$
 $\pm 6 \quad 0$
 $\pm 7 \quad 0$
 $\pm 9 \quad -1$
 $\pm 8 \quad 0$
 $\pm 24 \quad -6$
 $\pm 16 \quad -5$
 $\pm 6 \quad 0$
 $\pm 17 \quad -2$
 $\pm 9 \quad -1$
 $\pm 9 \quad -1$
 $\pm 6 \quad 3$
 $\pm 5 \quad 0$
 $\pm 6 \quad 1$
 $\pm 9 \quad -1$
 $\pm 7 \quad 0$
 $\pm 5 \quad 0$
 $\pm 6 \quad 2$
 $\pm 5 \quad 1$

$\pm 10 \quad -2$
 $\pm 8 \quad 0$
 $\pm 9 \quad -1$
 $\pm 16 \quad 2$
 $\pm 7 \quad -1$
 $\pm 6 \quad 1$
 $\pm 9 \quad 0$
 $\pm 5 \quad 0$
 $\pm 11 \quad 0$
 $\pm 6 \quad -4$
 $\pm 6 \quad -1$
 $\pm 8 \quad 0$
 $\pm 6 \quad 4$
 $\pm 6 \quad 1$
 $\pm 8 \quad -2$
 $\pm 9 \quad 1$
 $\pm 7 \quad 1$
 $\pm 8 \quad 3$
 $\pm 8 \quad 47$
 $\pm 7 \quad 26$
 $\pm 18 \quad -2$
 $\pm 11 \quad -1$
 $\pm 5 \quad 2$
 $\pm 6 \quad 0$
 $\pm 10 \quad -2$
 $\pm 8 \quad 61$
 $\pm 10 \quad 2$
 $\pm 8 \quad 1$
 $\pm 10 \quad 0$
 $\pm 8 \quad 0$
 $\pm 6 \quad 3$
 $\pm 5 \quad -3$
 $\pm 9 \quad 0$
 $\pm 7 \quad -3$
 $\pm 38 \quad 2$
 $\pm 6 \quad -2$

$\pm 9 \quad 0$
 $\pm 7 \quad 1$
 $\pm 11 \quad -3$
 $\pm 9 \quad 64$
 $\pm 9 \quad 2$
 $\pm 9 \quad -1$
 $\pm 6 \quad 0$
 $\pm 6 \quad -1$
 $\pm 11 \quad -2$
 $\pm 9 \quad 1$
 $\pm 8 \quad 0$
 $\pm 11 \quad -2$
 $\pm 12 \quad 0$
 $\pm 5 \quad -1$
 $\pm 9 \quad -4$
 $\pm 9 \quad 0$
 $\pm 10 \quad 2$
 $\pm 9 \quad -1$
 $\pm 10 \quad -1$
 $\pm 6 \quad 0$
 $\pm 7 \quad 0$
 $\pm 7 \quad 1$
 $\pm 6 \quad -1$
 $\pm 11 \quad 0$
 $\pm 9 \quad 44$
 $\pm 7 \quad 0$
 $\pm 13 \quad -3$
 $\pm 5 \quad 4$
 $\pm 6 \quad 0$
 $\pm 9 \quad -1$
 $\pm 6 \quad -2$
 $\pm 6 \quad -1$

tion method