# Cryptic recycling of continental crust during subduction of extended arcs and margins in Paleozoic Japan

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**ABSTRACT**
Continental crust is the archive of Earth's geological history, but its preservation is strongly imbalanced: although more than 65% of the present continental mass formed before 3 Ga, less than 5% of exposed crust is older than this age. Mass balance estimates indicate that two to four times the present continental mass has been recycled into the mantle over Earth history (6 to 12 × $10^{22}$ kg). Proposed recycling processes, including subduction erosion, sediment subduction, delamination, and continental subduction, collectively account for only a fraction of the flux required to maintain long-term mass balance. Here, we document an episode of efficient continental crust recycling along the Paleozoic margin of Japan. Zircon geochemistry from rare pre-Mesozoic granitoids records one, and possibly two, Paleozoic episodes of continental destruction. These data record a shift from mixed to juvenile isotopic signatures, consistent with the loss of an evolved crustal component in magma generation and its replacement by mantle-derived magmatism. We interpret this transition as recording efficient recycling of fragmented continental crust during back

# *1. Sample Description*

## *1.1 Cambrian*

**SHO – Shobouji Diorite (N39°04′34″, E141°14′19″), 495.9 ± 1.9 Ma (SF 1)**

A sample from the Shoboji quartz diorite was collected. These igneous rocks crop out in the vicinity of the Motai metamorphic unit (Wallis et al., 2020) in the South Kitakami (Pastor-Galán et al., 2021), but they appear to be unaffected by metamorphism. Consequently, the contact between the quartz diorite and the surrounding metamorphic rocks is generally interpreted as a fault. Previously reported zircon U–Pb ages cluster between 490 and 500 Ma(Isozaki et al., 2015), consistent with an Early Paleozoic magmatic event. We calculated the average age with 50 zircon and obtained a mean = 495.9 ± 1.9 Ma (50/50) MSWD = 0.71, p($\chi$2) = 0.94. Hafnium isotopic analyses of the SHO sample yield positive εHf values ranging from +9 to +15, indicating a juvenile source.

**HIT – Hitachi Tonalite (36.645961, 140.66598), 499.4 ± 1.4 Ma (SF 2)**

We collected a (meta-)tonalite from the Hitachi metamorphic unit in Ibaraki Prefecture. This unit occupies the southernmost part of the Abukuma Terrane and is composed of Early to Late Paleozoic sedimentary, volcanic, and associated intrusive rocks that have been metamorphosed predominantly under epidote–amphibolite facies conditions (Wallis et al., 2020). The Abukuma and South Kitakami terranes share comparable lithological assemblages, suggesting a common tectonic affinity (see Pastor-Galán et al., 2021). Previously reported crystallization ages from igneous rocks in the area range between 490 and 510 Ma, indicating an Early Paleozoic magmatic event (Tagiri et al., 2011).

A total of 35 analyses were used to calculate a weighted mean age of 499.4 ± 1.4 Ma (2σ; MSWD = 11; n = 35/37; p($\chi^2$) ≈ 0). This result mimoc the range of previously reported ages. The observed dispersion may indicate prolonged igneous activity during the Cambrian, consistent with the overlying volcanic successions (Tagiri et al., 2011). Hafnium isotopic analyses of the HIT sample yield initial εHf values ranging from +8 to +13.

## *1.2 Ordovician-Silurian*

**ITSU – Itsukaichi Tonalite (35.452582, 139.142467), 448.7 ± 2.9 Ma (SF 3)**

A block was collected from a serpentinite mélange in Sakamoto-zawa (Akiruno, Tokyo). Previous work by (Sawada et al., 2020) reported zircon U–Pb ages of 442 ± 2 Ma and 440 ± 4 Ma from two samples at this locality.

Our sample contains a high proportion of discordant zircon grains (>5% discordance). A total of 19 analyses yield a weighted mean age of 448.7 ± 2.9 Ma (2σ; MSWD = 6.9; p($\chi^2$) ≈ 0). Initial εHf values range from −5 to +5 and overlap with other Silurian sources, such as the Hikami Granite (e.g., Pastor-Galán et al., 2021). The surrounding region experienced multiple metamorphic events during the Carboniferous and Cretaceous and has been affected by prolonged magmatic and metasomatic activity (e.g., Pastor-Galán et al., 2021), which likely contributed to the observed zircon discordance. Nevertheless, the obtained age is consistent with previously reported values.

**HAYA – Kagura Trondhjemite (39.535014, 141.625197), ), 467.7 ± 1.6 Ma (SF 4)**

The South Kitakami belt contain two ophiolitic units: the Miyamori and Hayachine Complexes (Ishiwatari et al., 2016). The Miyamori Complex is primarily composed of harzburgite and dunite, whereas the Hayachine Complex is dominated by lherzolite. Geochemical analyses indicate that the Miyamori Complex formed in a forearc environment, while the Hayachine Complex developed in a back-arc setting (Ishiwatari et al., 2016), suggesting that these ophiolites originated within an island arc system (Ozawa et al., 2015; Uchino and Kawamura, 2016). Zircon U–Pb ages of approximately 470–450 Ma obtained from the Hayachine Complex indicate an Ordovician formation age (Shimojo et al., 2010), consistent with the age of the overlying sedimentary sequence.

Our sample from the Kagura Trondhjemite yielded a U–Pb zircon age of 467.7 ± 1.6 / 5.4 Ma (n = 30/32; MSWD = 11; $p(\chi^2) = 0$), consistent with the previously reported age on the same locality of 466 ± 6 Ma (Shimojo et al., 2010). The εHf values range from +12 to +16, indicating a highly juvenile signature, largely derived from a depleted mantle source with minimal crustal contribution.

**HY 1 – Cobble from Orikabetoge Formation (39.521730, 141.340895, 448.7 ± 2 Ma (SF 5)**

We collected a cobble from a conglomerate of the Orikabetoge Formation in the vicinity of the Hayachine metamorphic complex (Wallis et al., 2020). The Orikabetoge Formation consists of conglomerates, arkoses, and mudstones, with subordinate limestone and tuff, and contains a rich assemblage of Silurian corals and trilobites (see Pastor-Galán et al., 2021). The conglomerates include abundant granitic clasts that are lithologically similar to the Hikami Granite.

U–Pb zircon analyses yielded a mean age of 448.7 ± 2.0 / 6.2 Ma (n = 18/19; MSWD = 8; $p(\chi^2) = 0$), which is consistent with ages reported for the Hikami Granite (Pastor-Galán et al., 2021, and references therein) and the ITSU sample. The εHf values range from −9 to +2, overlapping with those documented for both the Hikami Granite and the Itsukaichi tonalite.

## *1.3 Carboniferous-Permian*

**Wariyama and Takase granites (SF 6-10)**

The *Wariyama Sheared Granodiorite* was originally described as a single plutonic body occurring along the eastern side of the Futaba Fault in the Abukuma Mountains. A detailed re-examination by (Tsuchiya et al., 2014) show that this unit consists of two distinct plutonic bodies of different ages. The older unit, now termed the Wariyama Granite, forms the main N–S elongated body and is of late Carboniferous age (ca. 308–302 Ma). The younger unit, defined as the Takase Granite, crops out along the eastern side of the Wariyama body, where it occurs in faulted contact as a narrow, elongated belt and shows an age of ca 115-120 Ma. These relationships are well exposed in quarry outcrops, where the boundary between the two units is marked by mylonitized zones and incorporates a variety of associated lithologies, including metadiorite, metasandstone, skarn, and metamorphic rocks.

We collected samples four samples in two quarries. One of the quarries showed two distinct granitic bodies and the mylonitic boundary between them.

**WAR 2-1 (37.981804°, 140.853300°), (SF 6A)**

The sample was collected from an abandoned quarry. The sample contain a relatively high proportion of discordant zircon grains.. Our analyses yield a slightly younger mean U–Pb age than previously reported, at 288.0 ± 2.3 / 3.1 Ma (n = 26/27; MSWD = 1.7; p($\chi^2$) = 0.01; SF 7–9). The initial εHf values range from +9 to +13, indicating a dominantly juvenile signature.

**WAR 2 and WAR 2-4 (37.937111°, 140.856261°), (SF 6B)**

Both samples were collected from an active quarry, corresponding to the locality described by Tsuchiya et al. (2014). Our analyses yield slightly younger mean U–Pb ages than previously reported: WAR2 gives a mean age of 284.1 ± 1.7 Ma (n = 36/38; MSWD = 1.3; p($\chi^2$) = 0.13; SF 7–9), while WAR4-1 yields an identical mean age of 284.1 ± 1.7 Ma (36/38; MSWD = 1.3; p($\chi^2$) = 0.13).

The initial εHf values for both samples span +9 to +13, consistent with those obtained for WAR2-1, and indicate a dominantly juvenile signature.

**TAKASE**

We collected a sample from a distinct unit bounded by mylonitic faults, described by Tsuchiya et al. (2014) as the Takase Granite of Early Cretaceous age. However, our analyses reveal a high proportion of discordant zircon grains (SF 6–10). Only four concordant analyses (<5% discordance) yield a U–Pb age of 293.6 ± 5.2 Ma (MSWD = 0.51; p($\chi^2$) = 0.6), significantly older than the previously inferred emplacement age.

The initial εHf values range from +9 to +13, consistent with those obtained for the Wariyama samples, indicating a similarly juvenile signature. Furthermore, zircon characteristics, including age patterns and geochemical signatures, are indistinguishable across all samples. The TAKASE sample also closely resembles WAR2-1 in terms of zircon behavior.

These observations suggest that the sampled unit is more likely part of the Wariyama batholith rather than a distinct Early Cretaceous intrusion. We propose that the presence of younger Mesozoic intrusions in the area may have contributed to the high degree of zircon discordance observed in some samples.

**KIN – Kinsho-zan Diorite (36°03.85', 139°14.97'E), 281.2 ± 1.6 Ma (SF 11)**

The Kinshozan Quartz Diorite occurs in the Yorii area, located in the northeastern part of the Kanto Mountains, Japan (Ogasawara et al., 2016). This region belongs to the Sambagawa and Chichibu Belts of the Outer Zone of Southwest Japan (Wallis et al., 2020). A quartz diorite sample was collected from the Atagura Klippe (Kabutogawa, Ogawa-machi, Saitama Prefecture). Ogasawara et al. (2016) reported a SHRIMP zircon U–Pb age of 281.5 ± 1.8 Ma. Our LA-ICP-MS zircon U–Pb age from 40 grains of 281.2 ± 1.6 Ma (MSWD = 0.45, p($\chi$2) = 1) is fully consistent with this previously reported age. Initial εHf values range from 10 to 15.

**AI1 and AI2 Cobles from Yamazaki (Usuginu) conglomerate (38.799006°, 141.289868°)**

The Yamazaki Permian Conglomerate, conformably overlies the Tenjinnoki Formation and it is known for containing coble to boulder-size granitic clasts (Li and Takeuchi, 2022) and references therein). We sampled two distinct cobles from the conglomerate at the Aikawa dam. Previous ages included bulk rock K-Ar and CHIMES and gave ranges between 225 to 280 Ma (mostly younger than the conglomerate age, which is middle Permian).

**AI1, 299.6 ± 1.1 (SF 12)** yields a latest Carboniferous to earliest Permian U–Pb zircon age of 299.6 ± 1.1 (n = 28; MSWD = 5.8; $p(\chi^2) = 0$).

**AI2, 290.08 ± 0.85 (SF 13)** provides a slightly younger but comparable age of 290.08 ± 0.85 / 3.06 Ma (n = 39; MSWD = 12; $p(\chi^2) = 0$). In both samples, εHf values range from +9 to +15, indicating a consistently juvenile isotopic signature.

**References:**


Ishiwatari, A., Ozawa, K., Arai, S., Ishimaru, S., Abe, N., Takeuchi, M., 2016. Ophiolites and ultramafic rocks, in: Moreno, T., Wallis, S., Kojima, T., Gibbons, W. (Eds.), The Geology of Japan. Geological Society London, pp. 223–250. https://doi.org/10.1144/GOJ.9

Isozaki, Y., Ehiro, M., Nakahata, H., Aoki, K., Sakata, S., Hirata, T., 2015. Cambrian plutonism in Northeast Japan and its significance for the earliest arc-trench system of proto-Japan: New U-Pb zircon ages of the oldest granitoids in the Kitakami and Ou Mountains. Journal of Asian Earth Sciences 108, 136–149. https://doi.org/10.1016/j.jseaes.2015.04.024

Li, Y., Takeuchi, M., 2022. U–Pb dating of detrital zircon from Permian successions of the South Kitakami Belt, Northeast Japan: Clues to the paleogeography of the belt. Island Arc 31, e12435. https://doi.org/10.1111/iar.12435

Ogasawara M., Fukuyama M., Horie K., 2016. SHRIMP U–Pb zircon dating of the Kinshozan Quartz Diorite from the Kanto Mountains, Japan: Implications for late Paleozoic granitic activity in Japanese Islands. Island Arc 25, 28–42. https://doi.org/10.1111/iar.12136

Ozawa, K., Maekawa, H., Shibata, K., Asahara, Y., Yoshikawa, M., 2015. Evolution processes of Ordovician–Devonian arc system in the South-Kitakami Massif and its relevance to the Ordovician ophiolite pulse. Island Arc 24, 73–118. https://doi.org/10.1111/iar.12100

Pastor-Galán, D., Spencer, C.J., Furukawa, T., Tsujimori, T., 2021. Evidence for crustal removal, tectonic erosion and flare-ups from the Japanese evolving forearc sediment provenance. Earth and Planetary Science Letters 564, 116893. https://doi.org/10.1016/j.epsl.2021.116893

Sawada H., Isozaki Y., Sakata S., 2020. Fragments of the early Paleozoic orogenic belt from Tokyo Metropolis, Japan: Zircon U-Pb ages of high P/T-type metagabbro and granitoids of the Kurosegawa belt in eastern Kanto Mountains. Jour. Geol. Soc. Japan 126, 551–561. https://doi.org/10.5575/geosoc.2020.0026

Shimojo, M., Otoh, S., Yanai, S., Hirata, T., Maruyama, S., 2010. LA-ICP-MS U-Pb Age of Some Older Rocks of the South Kitakami Belt, Northeast Japan. Journal of Geography (Chigaku Zasshi) 119, 257–269. https://doi.org/10.5026/jgeography.119.257

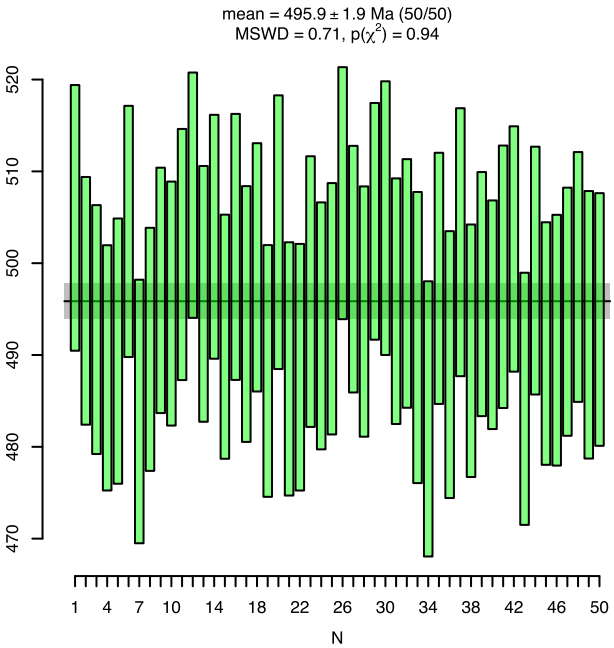
Tsuchiya, N., Takeda, T., Tani, K., Adachi, T., Nakano, N., Osanai, Y., Kimura, J.-I., 2014. Zircon U–Pb age and its geological significance of late Carboniferous and Early Cretaceous adakitic granites from eastern margin of the Abukuma Mountains, Japan. Jour. Geol. Soc. Japan 120, 37–51. https://doi.org/10.5575/geosoc.2014.0003

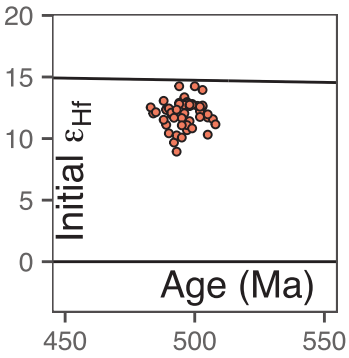
Uchino T., Kawamura M., 2016. Ordovician backarc-basin metadolerite and metabasalt of the South Kitakami Terrane, Northeast Japan. Island Arc 25, 274–286. https://doi.org/10.1111/iar.12151

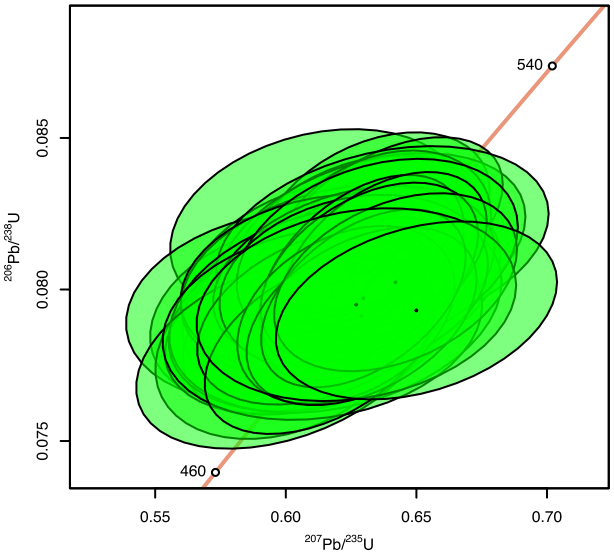
Wallis, S.R., Yamaoka, K., Mori, H., Ishiwatari, A., Miyazaki, K., Ueda, H., 2020. The basement geology of Japan from A to Z. Island Arc 29, e12339. https://doi.org/10.1111/iar.12339

**SF 1 - Shobouji Diorite (SHO)**

Synthesized results from the Shobouji diorite. Up-left sampled outcrop. Up-right weighted mean. Down-left, U-Pb vs εHf and down-right concordia plot.

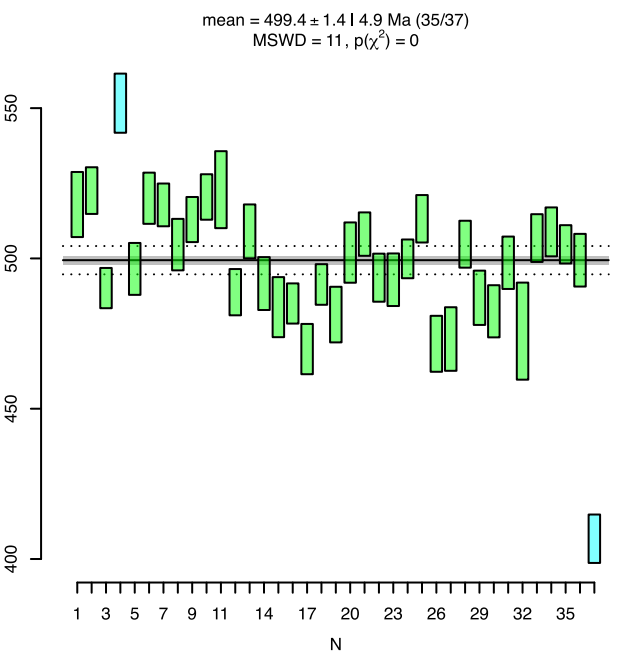

mean = 495.9 ± 1.9 Ma (50/50)
MSWD = 0.71, p(χ²) = 0.94
520
510
500
490
480
470
1 4 7 10 14 18 22 26 30 34 38 42 46 50
N

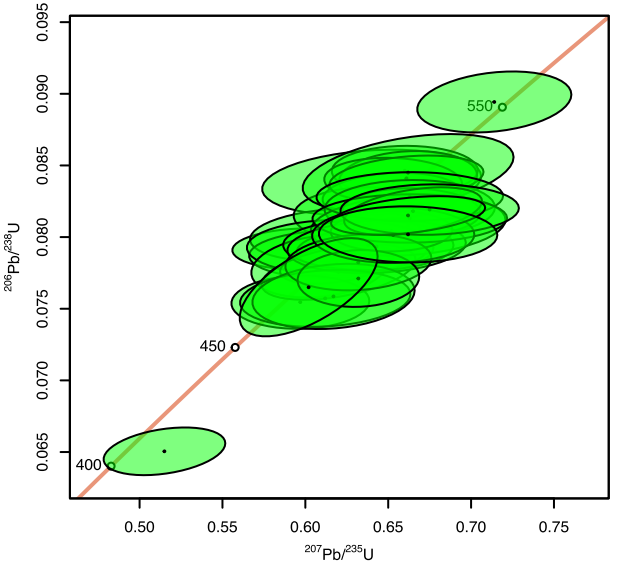

20
15
10
5
0
Initial εHf
Age (Ma)
450
500
550

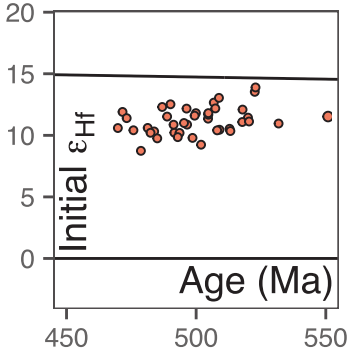

540
460
0.085
0.080
0.075
206Pb/238U
0.55
0.60
0.65
0.70
207Pb/235U

**SF 2 Hitachi Tonalite (HIT)**

Synthesized results from the Hitachi Tonalite. Up-left sampled outcrop and analyzed sample. Up-right weighted mean. Down-left, U-Pb vs εHf and down-right concordia plot.

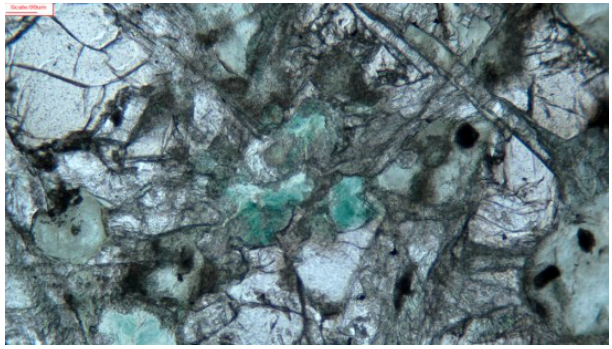

mean = 499.4 ± 1.4 | 4.9 Ma (35/37)
MSWD = 11 , p(χ2) = 0
550
500
450
400
1 3 5 7 9 11 14 17 20 23 26 29 32 35
N

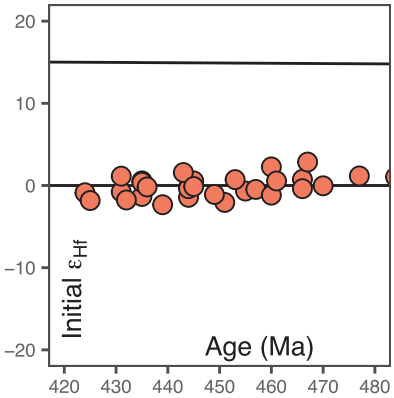

0.095
0.090
0.085
0.080
0.075
0.070
0.065
206Pb/238U
550
450
400
0.50 0.55 0.60 0.65 0.70 0.75
207Pb/235U

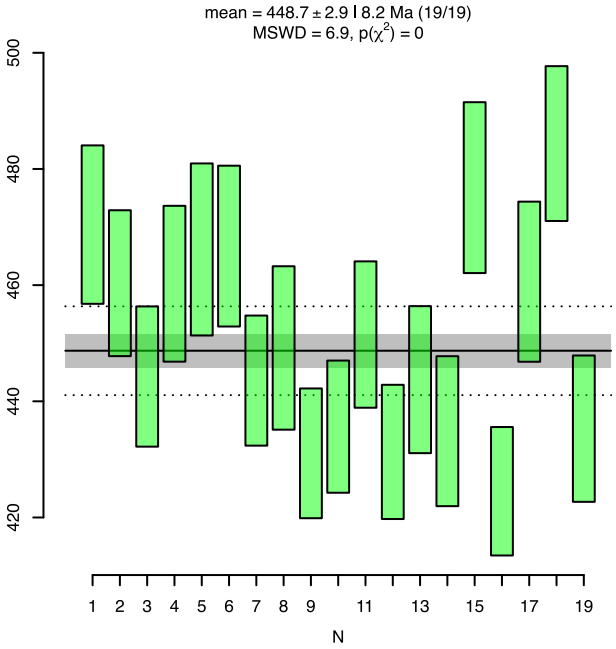

20
15
10
5
0
Initial εHf
Age (Ma)
450 500 550

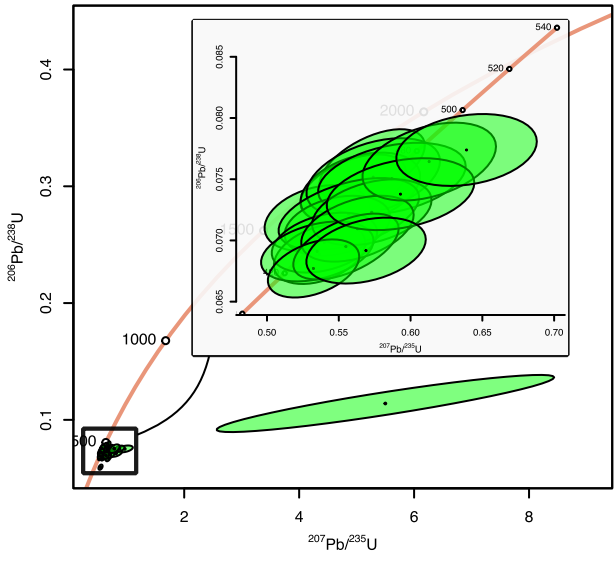
**SF 3 Itsukaichi Tonalite (ITSU)**

Up-left collected sample and thin section view. Up-right weighted mean. Down-left, U-Pb vs εHf and down-right concordia plot.



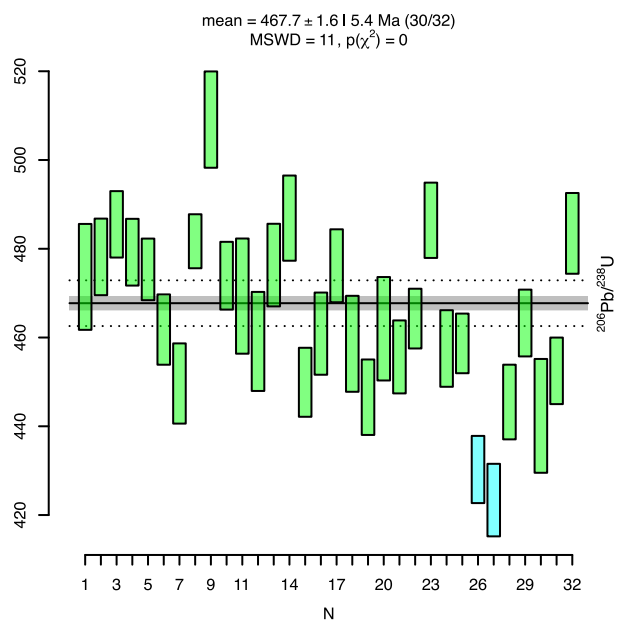

20
10
0
−10
−20
Initial εHf
Age (Ma)
420
430
440
450
460
470
480

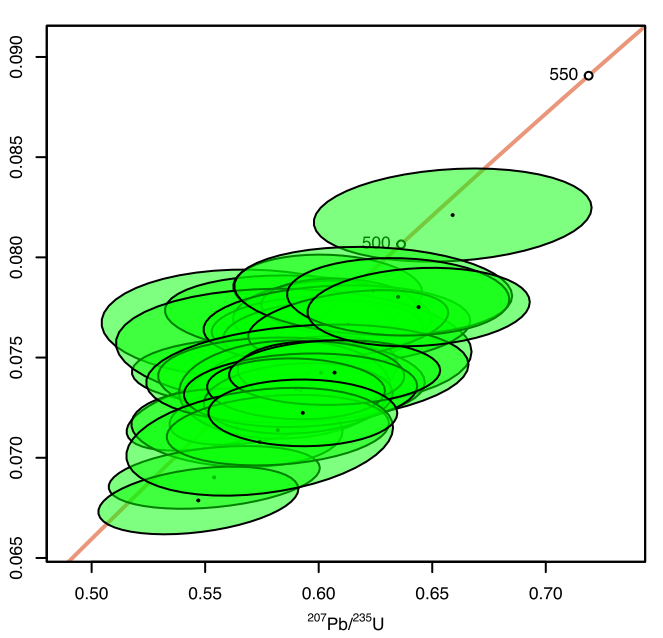

mean = 448.7 ± 2.9 I 8.2 Ma (19/19)
MSWD = 6.9, p(χ2) = 0
500
480
460
440
420
1
2
3
4
5
6
7
8
9
11
13
15
17
19
N

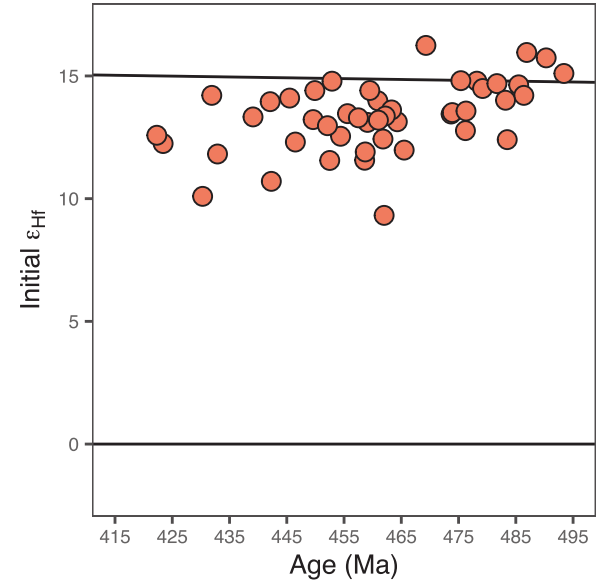

0.4
0.3
0.2
0.1
206Pb/238U
2
4
6
8
207Pb/235U
540
520
500
2000
1000
500
0.085
0.080
0.075
0.070
0.065
206Pb/238U
0.50
0.55
0.60
0.65
0.70
207Pb/235U

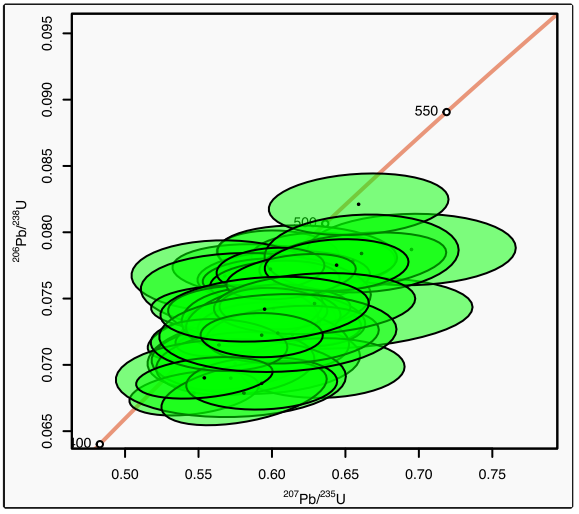
**SF 4 Kagura Trondhjemite (HAYA)**

Up-left weighted mean. Down-left, U-Pb vs εHf. Right concordia plot, up all zircon analyzed, down only concordant zircons..


mean = 467.7 ± 1.6 | 5.4 Ma (30/32)
MSWD = 11 , p(χ²) = 0
520
500
480
460
440
420
1 3 5 7 9 11 14 17 20 23 26 29 32
N
206Pb/238U

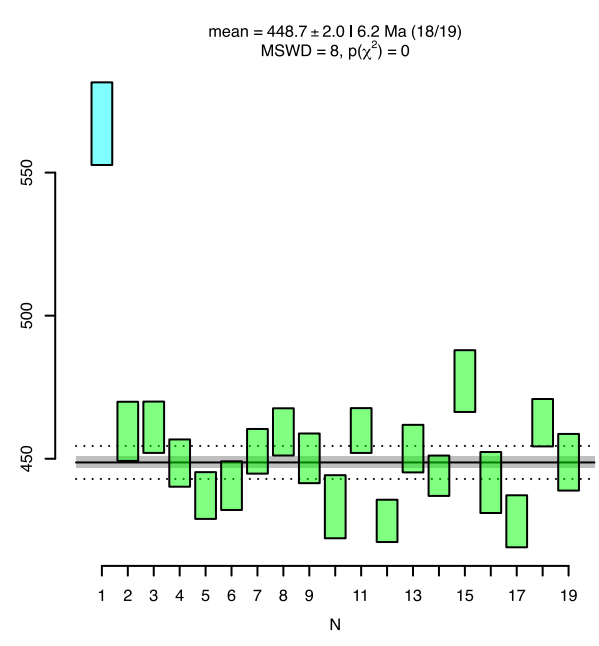

550
500
0.090
0.085
0.080
0.075
0.070
0.065
0.50 0.55 0.60 0.65 0.70
207Pb/235U

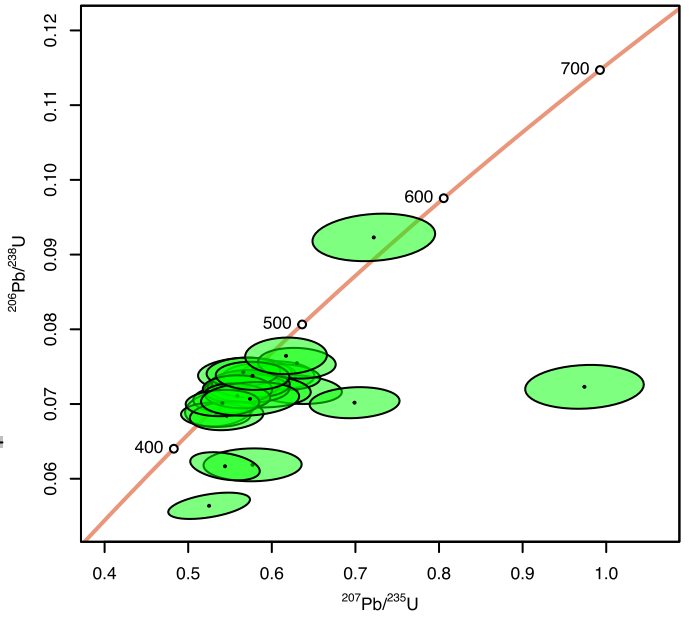

15
10
5
0
Initial εHf
415 425 435 445 455 465 475 485 495
Age (Ma)

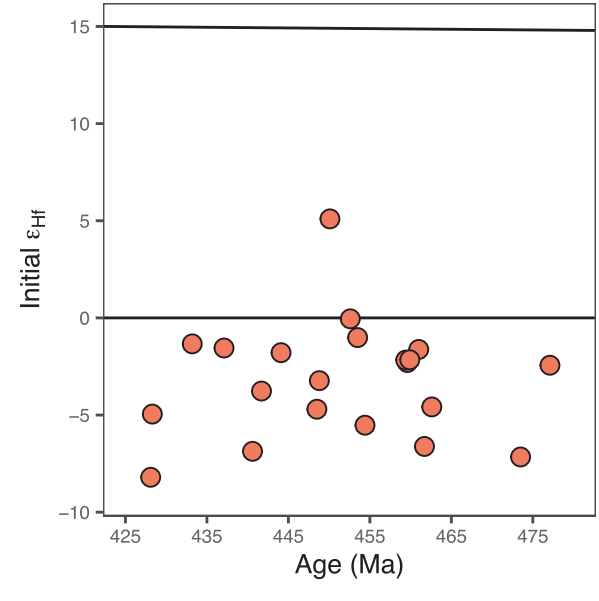

550
500
0.095
0.090
0.085
0.080
0.075
0.070
0.065
206Pb/238U
0.50 0.55 0.60 0.65 0.70 0.75
207Pb/235U

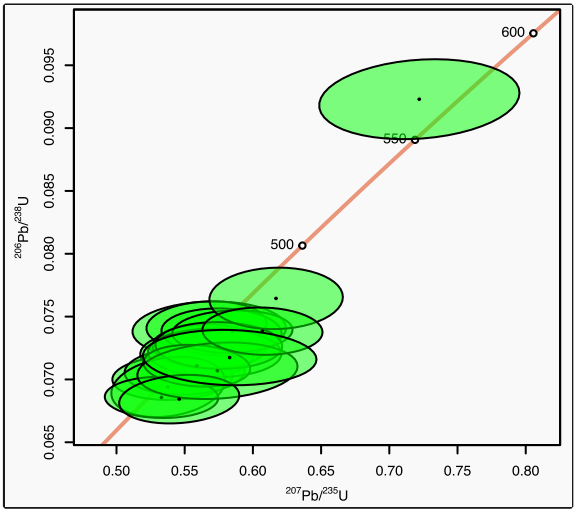
**SF 5 Cobble from Orikabetoge Formation (HY-1)**

Results from the analyzed cobble in the Orikabetoge conglomerate. Up-left weighted mean. Down-left, U-Pb vs εHf. Right concordia plot, up all zircon analyzed, down only concordant zircons.


mean = 448.7 ± 2.0 I 6.2 Ma (18/19)
MSWD = 8, p(χ²) = 0
550
500
450
1 2 3 4 5 6 7 8 9 11 13 15 17 19
N


700
600
500
400
0.12
0.11
0.10
0.09
0.08
0.07
0.06
206Pb/238U
0.4 0.5 0.6 0.7 0.8 0.9 1.0
207Pb/235U


15
10
5
0
−5
−10
Initial εHf
425 435 445 455 465 475
Age (Ma)


600
550
500
0.095
0.090
0.085
0.080
0.075
0.070
0.065
206Pb/238U
0.50 0.55 0.60 0.65 0.70 0.75 0.80
207Pb/235U

## SF 6 – Abukuma Quarries (Wariyama and Takase)

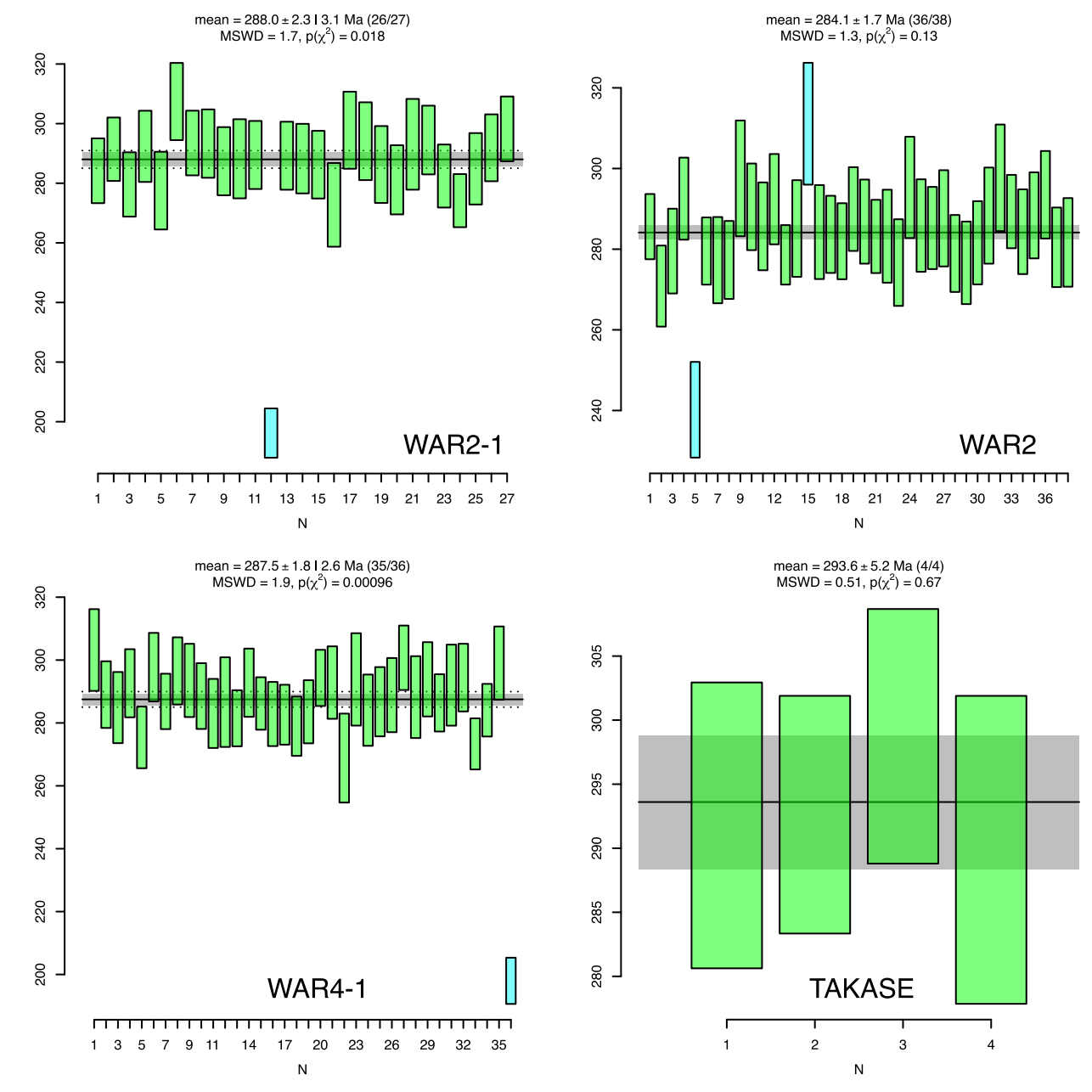
A) Sample locality of WAR 2-1
B) Sample locality of WAR 2, WAR 2-4 and TAKASE


A)


B)

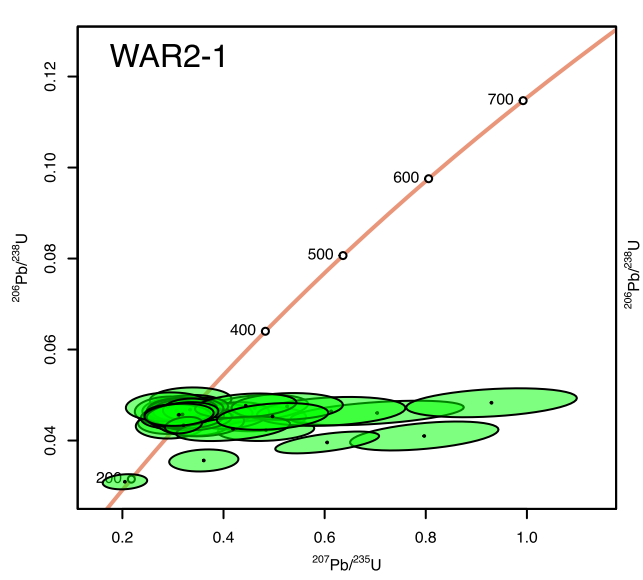
**SF 7 – Average results of the samples from Abukuma Quarries (Wariyama and Takase)**

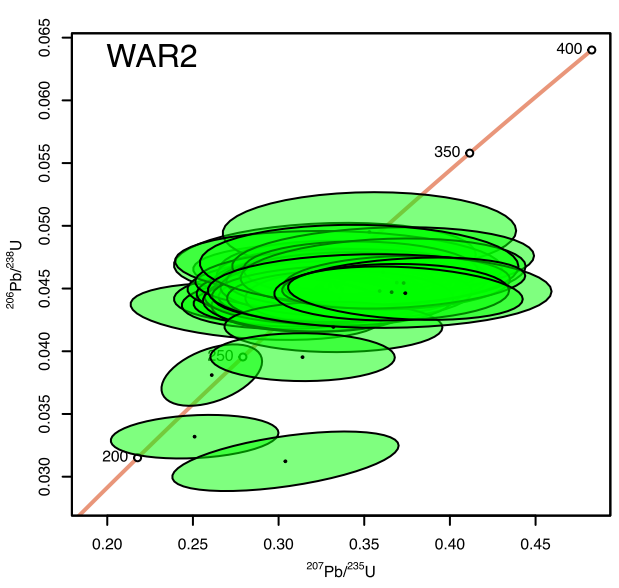
Average resultsof each of the samples collected in the Abukuma mountains.

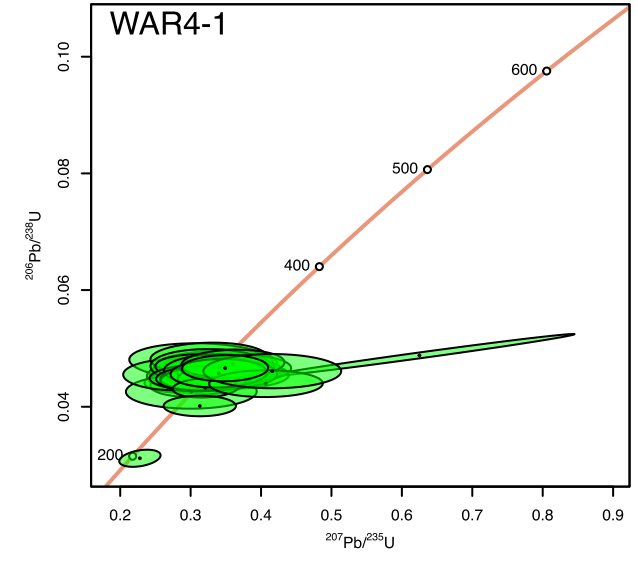

mean = 288.0 ± 2.3 | 3.1 Ma (26/27)
MSWD = 1.7, p(χ2) = 0.018
WAR2-1
N
mean = 284.1 ± 1.7 Ma (36/38)
MSWD = 1.3, p(χ2) = 0.13
WAR2
N
mean = 287.5 ± 1.8 | 2.6 Ma (35/36)
MSWD = 1.9, p(χ2) = 0.00096
WAR4-1
N
mean = 293.6 ± 5.2 Ma (4/4)
MSWD = 0.51, p(χ2) = 0.67
TAKASE
N

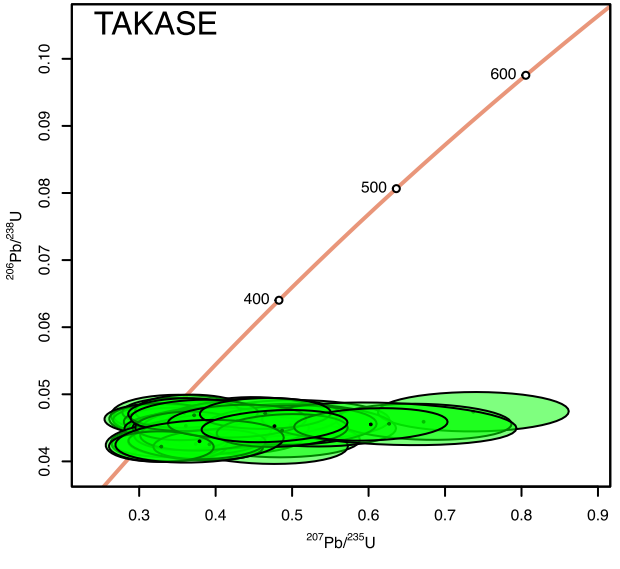
**SF 8 Concordia plots for WAR and TAKASE**

Concordia plots of the samples taking in the Abukuma mountains.


WAR2-1
700
600
500
400
200
0.12
0.10
0.08
0.06
0.04
0.2
0.4
0.6
0.8
1.0
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$

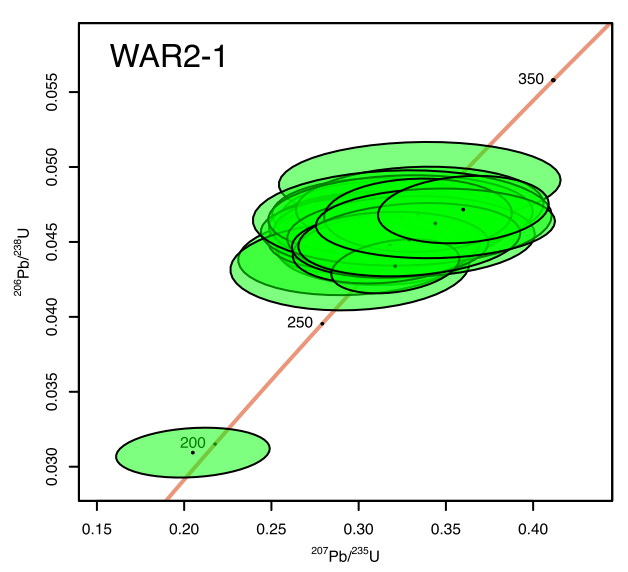

WAR2
400
350
250
200
0.065
0.060
0.055
0.050
0.045
0.040
0.035
0.030
0.20
0.25
0.30
0.35
0.40
0.45
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$

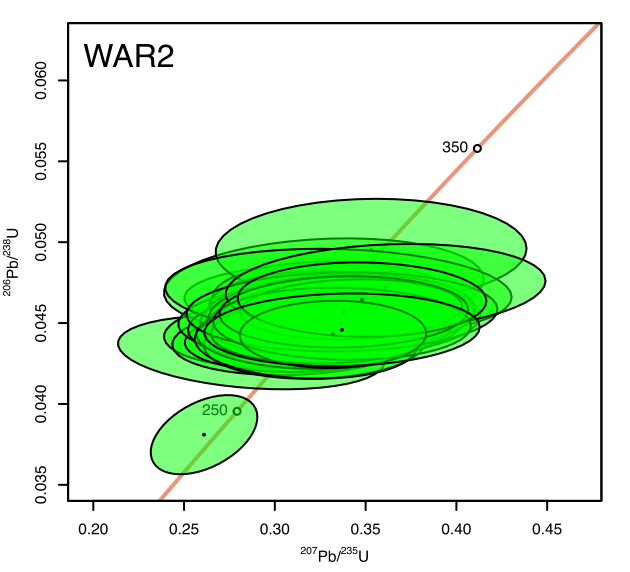

WAR4-1
600
500
400
200
0.10
0.08
0.06
0.04
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$

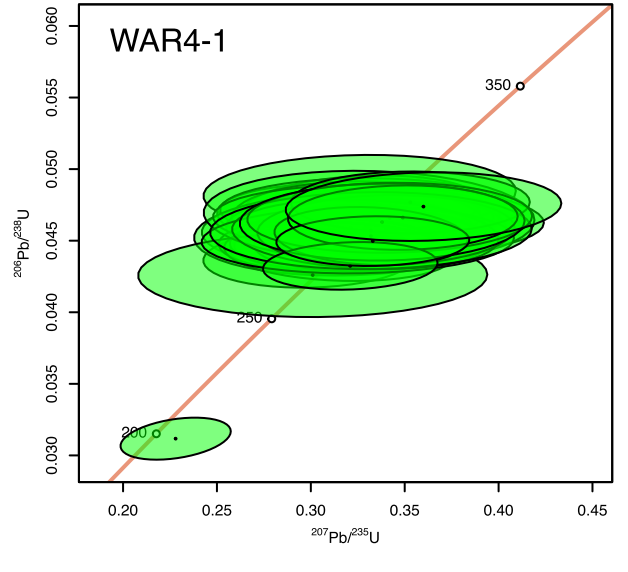

TAKASE
600
500
400
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.3
0.4
0.5
0.6
0.7
0.8
0.9
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$

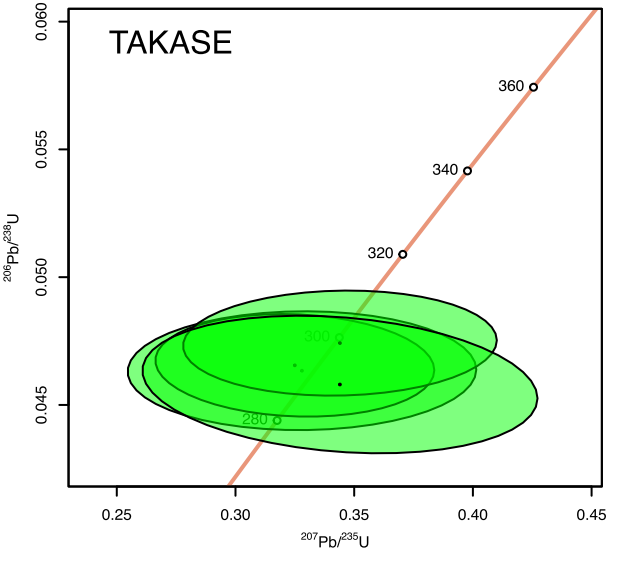
**SF 9 Concordia plots of WAR and Takase without discordant zircon grains**

This figure shows as SF 8, but only concordant grains.


WAR2-1
350
250
200
0.055
0.050
0.045
0.040
0.035
0.030
0.15
0.20
0.25
0.30
0.35
0.40
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$

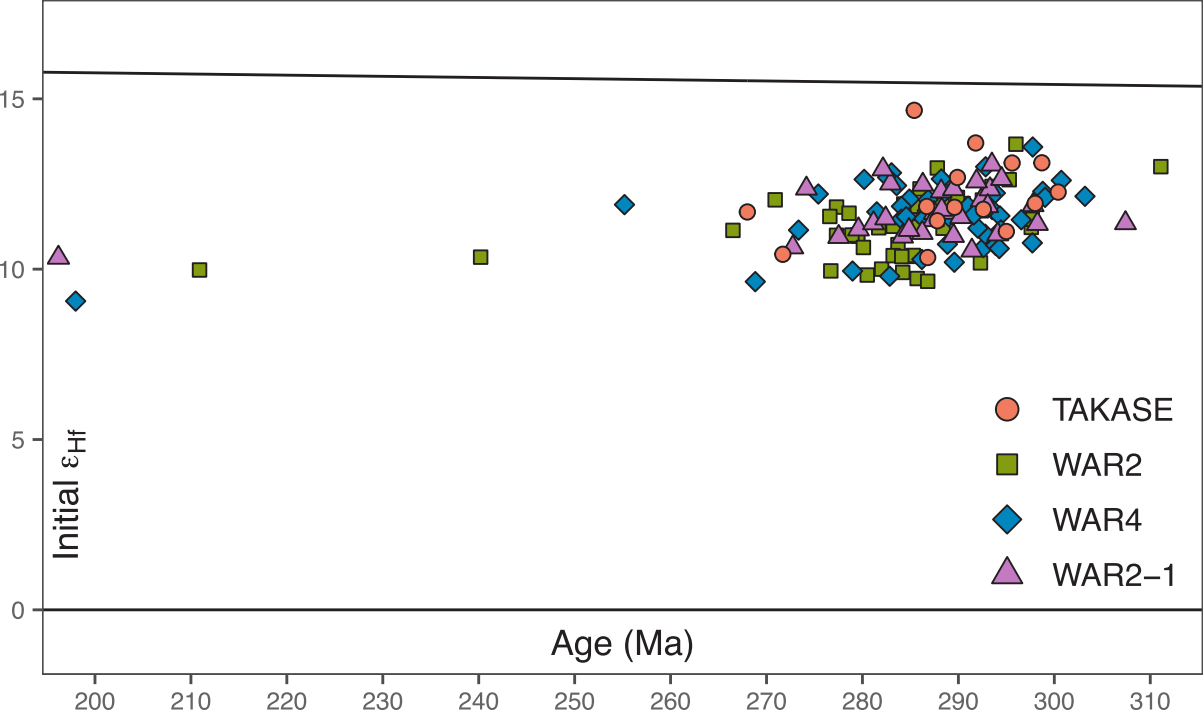

WAR2
350
250
0.060
0.055
0.050
0.045
0.040
0.035
0.20
0.25
0.30
0.35
0.40
0.45
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$


WAR4-1
350
250
200
0.060
0.055
0.050
0.045
0.040
0.035
0.030
0.20
0.25
0.30
0.35
0.40
0.45
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$


TAKASE
360
340
320
300
280
0.060
0.055
0.050
0.045
0.25
0.30
0.35
0.40
0.45
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$

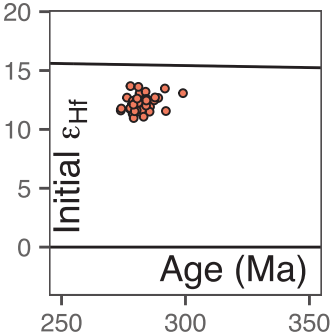
**SF 10 – U Pb vs εHf in the Abukuma Quarries (Wariyama and Takase)**

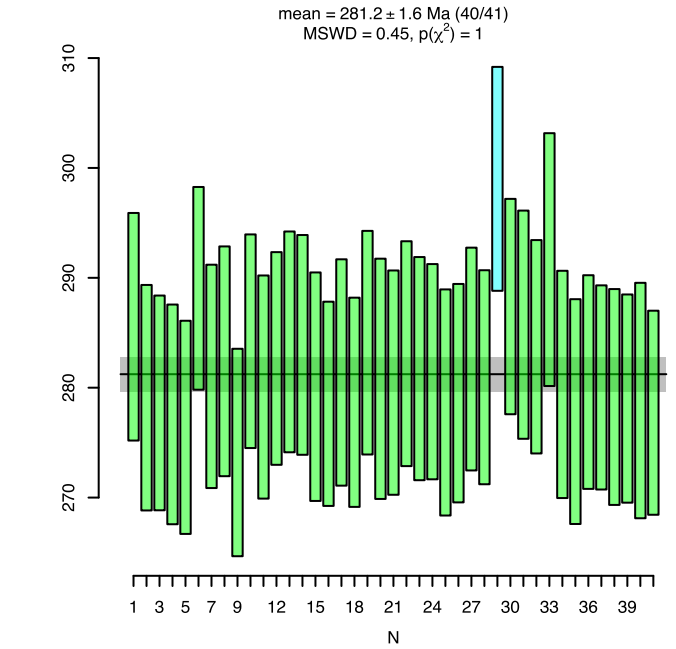
Plots show WAR and TAKASE samples.

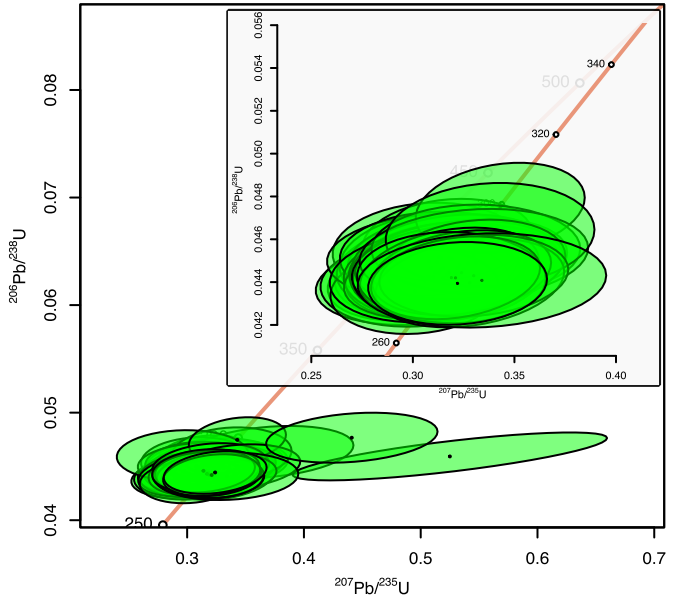

15
10
5
0
Initial εHf
Age (Ma)
200
210
220
230
240
250
260
270
280
290
300
310
TAKASE
WAR2
WAR4
WAR2–1

**SF 11 Kinsho-zan Diorite (KIN)**

Up-left sampled outcrop and analyzed sample. Up-right weighted mean. Down-left, U-Pb vs εHf and down-right concordia plot.

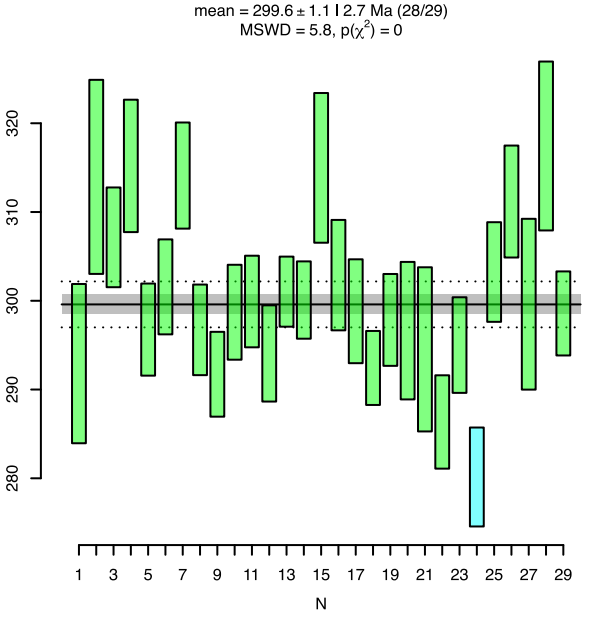

20
15
10
5
0
Initial $\varepsilon_{Hf}$
Age (Ma)
250
300
350

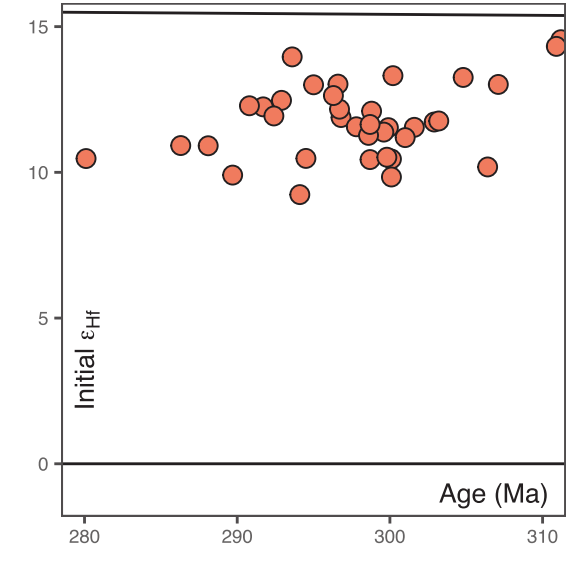

mean = 281.2 ± 1.6 Ma (40/41)
MSWD = 0.45, p($\chi^2$) = 1
310
300
290
280
270
1 3 5 7 9 12 15 18 21 24 27 30 33 36 39
N

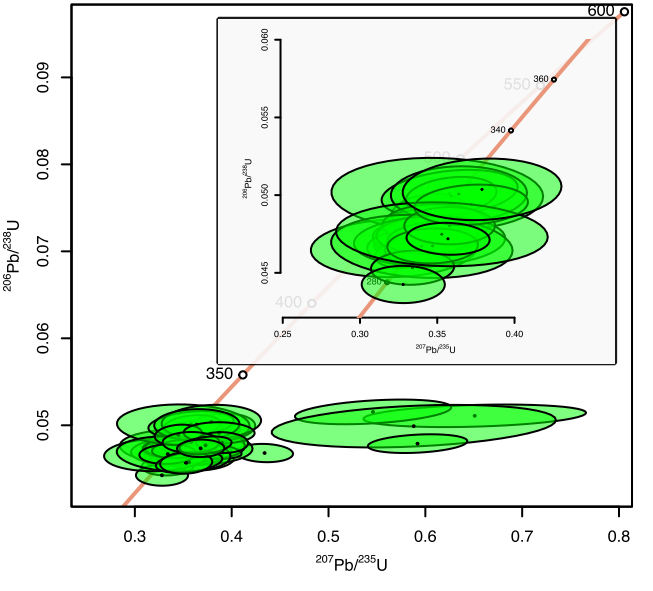

$^{206}Pb/^{238}U$
0.08
0.07
0.06
0.05
0.04
0.3
0.4
0.5
0.6
0.7
$^{207}Pb/^{235}U$
340
320
260
250
500
350
$^{206}Pb/^{238}U$
0.056
0.054
0.052
0.050
0.048
0.046
0.044
0.042
0.25
0.30
0.35
0.40
$^{207}Pb/^{235}U$

**SF 12 AI1 Cobble from Yamazaki (Usuginu) conglomerate**

Up-left sampled outcrop. Up-right weighted mean. Down-left, U-Pb vs εHf and down-right concordia plot.

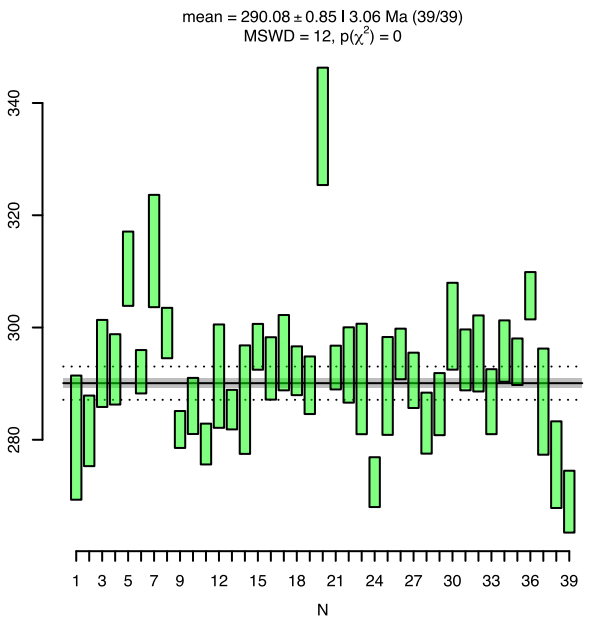

mean = 299.6 ± 1.1 | 2.7 Ma (28/29)
MSWD = 5.8, p(χ2) = 0
320
310
300
290
280
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29
N

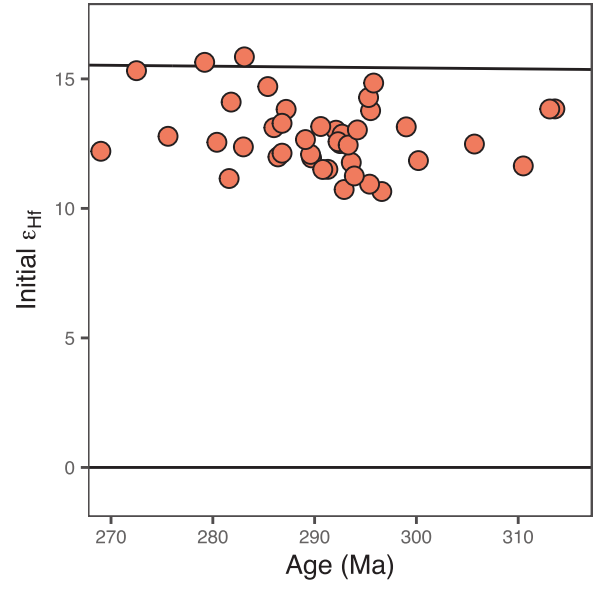

15
10
5
0
Initial εHf
280 290 300 310
Age (Ma)

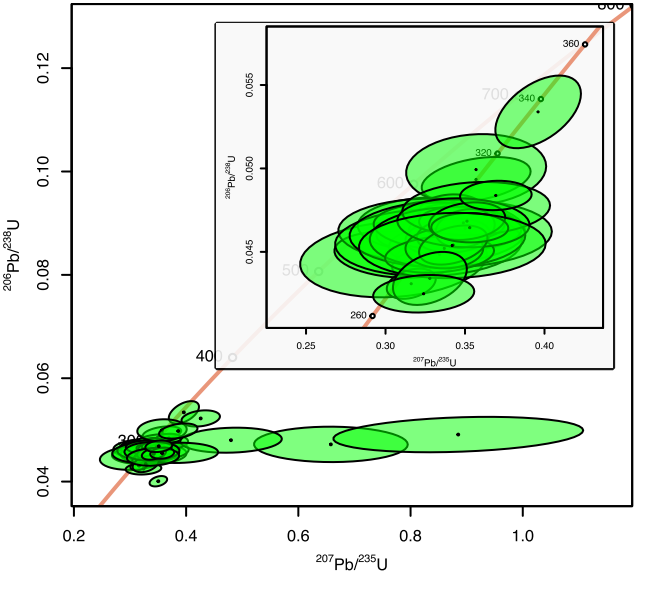

600
550
360
340
400
350
0.060
0.055
0.050
0.045
206Pb/238U
0.25 0.30 0.35 0.40
207Pb/235U
0.09
0.08
0.07
0.06
0.05
206Pb/238U
0.3 0.4 0.5 0.6 0.7 0.8
207Pb/235U

**SF 12 AI2 Cobble from Yamazaki (Usuginu) conglomerate**

Up-left sampled outcrop. Up-right weighted mean. Down-left, U-Pb vs εHf and down-right concordia plot.


mean = 290.08 ± 0.85 I 3.06 Ma (39/39)
MSWD = 12, p(χ²) = 0
340
320
300
280
1 3 5 7 9 12 15 18 21 24 27 30 33 36 39
N


Initial εHf
15
10
5
0
270 280 290 300 310
Age (Ma)


206Pb/238U
0.12
0.10
0.08
0.06
0.04
0.2 0.4 0.6 0.8 1.0
207Pb/235U
360
340
320
260
0.055
0.050
0.045
0.25 0.30 0.35 0.40

**SF 13 General geochemical results from the compiled dataset**

References:


Isozaki, Y., Ehiro, M., Nakahata, H., Aoki, K., Sakata, S. and Hirata, T., 2015. Cambrian plutonism in Northeast Japan and its significance for the earliest arc-trench system of proto-Japan: New U–Pb zircon ages of the oldest granitoids in the Kitakami and Ou Mountains. *Journal of Asian Earth Sciences*, *108*, pp.136-149.

Kawaguchi, K., Hayasaka, Y., Shibata, T., Komatsu, M., Kimura, K. and Das, K., 2020. Discovery of Paleozoic rocks at northern margin of Sambagawa terrane, eastern Kyushu, Japan: Petrogenesis, U–Pb geochronology and its tectonic implication. *Geoscience Frontiers*, *11*(4), pp.1441-1459.

Shimizu, H., Yoshimura, J.Y., Yamashita, M., Takahashi, K. and Adachi, M., 2000. Rb-Sr isotopic and REE geochemistry on garnet-biotite granodiorite clasts from the Permian Kozaki Formation, Kumamoto, Southwest Japan: A slightly enriched initial Sr isotope ratio and M-type REE tetrad pattern. *Geochemical Journal*, *34*(2), pp.101-120.

Adachi, M., Suzuki, K., Yogo, S. and Yoshida, S., 1994. The Okuhinotsuchi granitic mass in the South Kitakami terrane: pre-Silurian basement or Permian intrusives. *Journal of Mineralogy, Petrology and Economic Geology*, *89*(1), pp.21-36.

Tsuchiya, N., Takeda, T., Tani, K., Adachi, T., Nakano, N., Osanai, Y. and Kimura, J.I., 2014. Zircon U–Pb age and its geological significance of late Carboniferous and Early Cretaceous adakitic granites from eastern margin of the Abukuma Mountains, Japan. *The Journal of the Geological Society of Japan*, *120*(2), pp.37-51.

Suda, Y., 2004. Crustal anatexis and evolution of granitoid magma in Permian intra-oceanic island arc, the Asago body of the Yakuno ophiolite, Southwest Japan. *Journal of Mineralogical and Petrological Sciences*, *99*(5), pp.339-356.

Ikeda, K., 1994. Rb-Sr ages of the Yakuno rocks from the Northern subzone of the Maizuru Terrane, Kyoto Prefecture, Southwest Japan. *Journal of Mineralogy, Petrology and Economic Geology*, *89*, pp.443-454.