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U-Pb zircon ages for the Mitaki igneous rocks, Siluro-Devonian tuff, and granitic boulders in the Kurosegawa Terrane, Southwest Japan

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Abstract

Zircon U-Pb dating was carried out on three Mitaki igneous rocks, one silicic tuff of the Siluro-Devonian sequence, and three granitic boulders from the Kurosegawa Terrane in an effort to provide a framework of the plutonic-sedimentary history in the terrane. The Mitaki igneous rocks yield ages of 441.9 ± 4.5Ma, 441.5 ± 4.4Ma and 439.7 ± 10Ma. The silicic tuff is dated between 362.7 ± 1.7Ma and 414.1 ± 0.6Ma. Two granitic boulders from the Upper Permian Doi Formation are dated at 263.2 ± 4Ma and 250.8 ± 9.1Ma. A granitic boulder from the Middle Jurassic Kagio Formation gives an age of 203.5 ± 15Ma.

The results have led us to the conclusion that zircon U-Pb ages tend to indicate the intrusion of the Mitaki igneous rocks in the late Ordovician time; older than the age given by fossil records of the Siluro-Devonian sequence that overlies the Mitaki igneous rocks. The inherited component of a silicic tuff collected from the Siluro-Devonian sequence indicates that either the magmatic source was quite different from that both the Mitaki igneous rocks and the Permian granites represented in the conglomerates, or that old detrital zircon was incorporated into the tuff during sedimentation. The ages of the granitic boulders fall within the range of sedimentary ages for the conglomerates. This indicates rapid uplift and erosion soon after emplacement of the boulder protoliths, and rapid transport and deposition of conglomerate. The boulders might have been derived from the magmatic arc located in the South China or Indochina/East Malaya continental blocks in which the Mitaki igeneous rocks were involved as a crystalline basement.

Key words: Kurosegawa Terrane, Mitaki igneous rocks, granitic clast, U-Pb zircon age, Ordovisian crystalline basement, Permian magmatic arc, South China Block, Indochina/East Malaya Block, Gondwanaland

INTRODUCTION

Most granitic rocks in the Japanese Islands are Mesozoic and Tertiary in age, but “older granitic rocks” have been known to occur in localities such as the Hida-Oki and South Kitakami Terranes. One such example in the Outer Zone (Pacific side) of Southwest Japan is the Mitaki igneous rocks (Ichikawa et al., 1956) in the Kurosegawa Terrane (Fig. 1). They consist of cataclastic granitoids and occur as tectonic blocks in a serpentinite-matrix melange (Kurosegawa Tectonic Zone) in the Kurosegawa Terrane. Such tectonic blocks are commonly subjected to multiple metamorphic and deformational events and therefore are likely to have had a complex thermal history. A late Early Silurian to Upper Devonian sequence, which is the oldest geologic unit so far dated by fossils in the Outer Zone of Southwest Japan, unconformably cover the Mitaki igneous rock. Thus it has been thought that the emplacement of the Mitaki igneous rocks must predate early Silurian. The previous radiometric ages of the Mitaki igneous rocks dated by K-Ar, Rb-Sr and fission-track methods are mostly younger than the expected age (e.g., Hayase and Ishizaka, 1967; Kawano and Ueda, 1966; Shibata, 1968; Shima et al., 1969). The age of the Mitaki igneous rocks is yet to be strictly determined as cited above.

The Early Permian to Middle Jurassic formations in the Kurosegawa Terrane often have intercalated intraformational conglomerates containing granitic clasts. On the basis of the close field as-

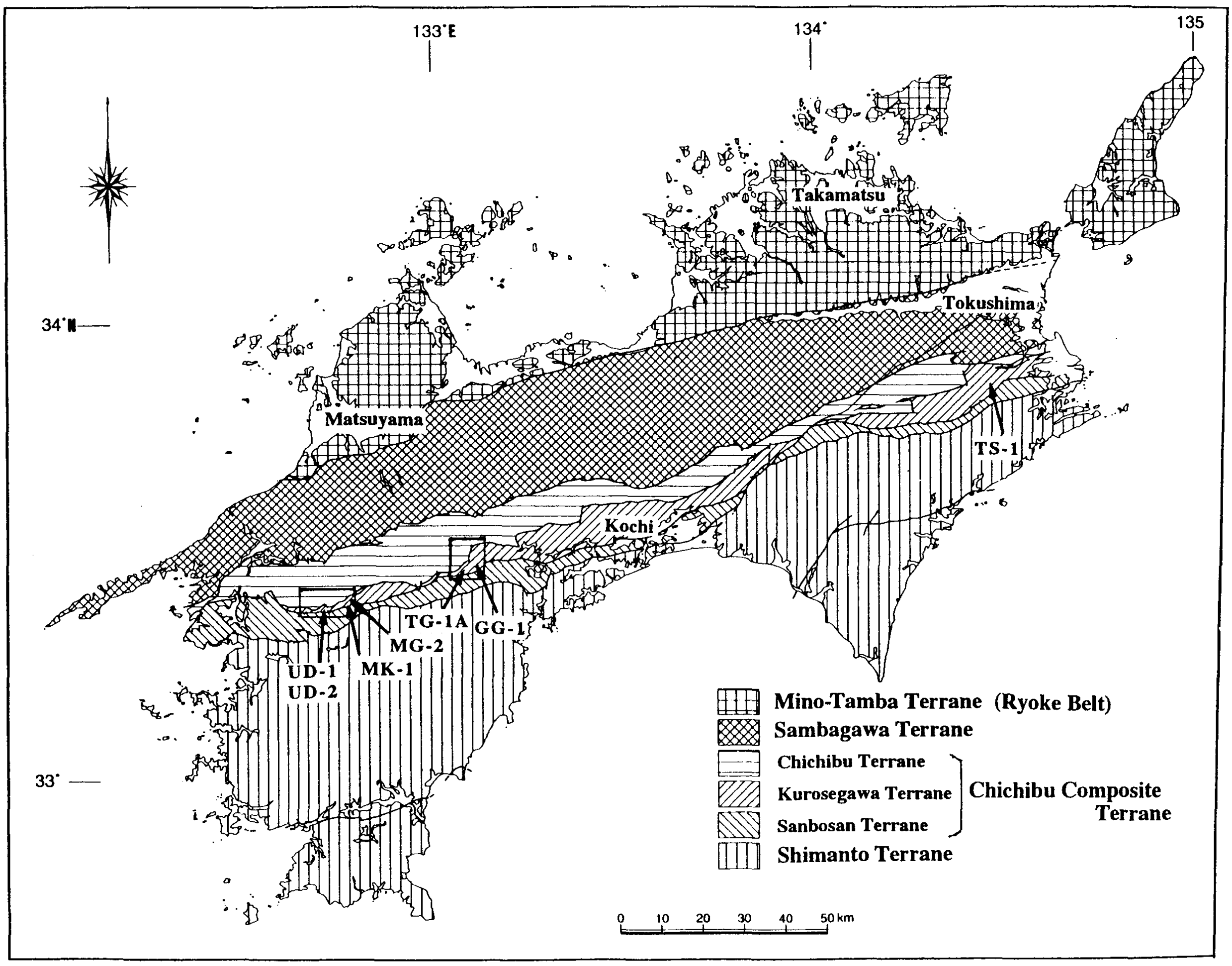

Fig. 1. Lithotectonic terrane map of Shikoku, Japan indicating the sample localities discussed in this paper.

sociation and petrographical similarities, Kano (1971) suggested that the granitic clasts might have been derived from the Mitaki igneous rocks. Though the age and provenance of the granitic clasts are critical to understanding the Paleozoic to Mesozoic evolution of the Kurosegawa Terrane, they have not previously been dated.

The Kurosegawa Terrane is a key component of Southwest Japan and appears to play an important role in development of the Japanese Islands. The lack of precise age determinations hampered better understanding of tectonic setting and origin of the Kurosegawa Terrane. This paper presents results of U-Pb zircon dating on three Mitaki igneous rocks, one Siluro-Devonian tuff, and three granitic boulders from the conglomerates in the Upper Permian Doi Formation and the Middle Jurassic Kagio Formation in Shikoku Island for determination of reliable crystallization ages. Sample localities are shown in Figs. 1, 3 and 4. The results have led us to profound revisions in the tectonic framework of the Outer Zone of Southwest Japan. The geologic time scale 1989 of Harland et al. (1990) is used throughout. Major- and minor-element analyses of the Mitaki igneous rocks and granitic boulders in the Kurosegawa Terrane including the samples used for this study were carried out by one of the present authors (S. Y.) and were reported in Hada (1990).

GEOLOGY OF THE KUROSEGAWA TERRANE

The geology of the Kurosegawa Terrane has been well documented, and only brief descriptions will be outlined below; for further details, the reader is referred to Yoshikura et al. (1990) and references therein. The Kurosegawa Terrane is a disrupted, composite terrane bounded to the north by the Mesozoic Chichibu Terrane and to the south by the Mesozoic Sanbosan Terrane both of which are widely interpreted as subduction complex (Hada and Yoshikura, 1991) (Fig. 1). It is semicontinuously exposed for more than 1,000km long parallel to the general E-W strike of the Outer Zone of Southwest Japan. The boundary with adjacent terranes is marked over much of its length by regional faults and abrupt changes in lithologies. The terrane is made up of the Kurosegawa Tectonic Zone, a late Permian accretionary complex and its metamorphic equivalents, and covering strata of late Paleozoic, Triassic, and Jurassic ages.

The Kurosegawa Tectonic Zone is a serpentinite-matrix melange consisting of fault-bound blocks of diverse lithologies, sizes, shapes and ages enclosed wholly or partly in a highly sheared serpentinite. The representative lithologies of the tectonic blocks occurring in the Kurosegawa Tectonic Zone are granitic rocks (Mitaki igneous rocks), high-grade metamorphic rocks (Terano metamorphic rocks), Siluro-Devonian sequence, and high P/T metamorphic rocks. The Mitaki igneous rocks are medium- to coarse-grained granitic rocks, and their compositions vary from diorite to granite, with granodiorite being the dominant lithology. They were subjected to cataclasis and subgreenschist-facies metamorphism. The Terano metamorphic rocks were metamorphosed under amphibolite- to granulite-facies conditions probably during Silurian time (Yoshikura et al., 1981). The Mitaki igneous rocks and Terano metamorphic rocks are generally regarded as representing the basement complex upon which the Silurian-Devonian sequence was deposited. The Siluro-Devonian sequence consists dominantly of continental margin volcanic arc-derived silicic volcaniclastic rocks with minor intercalations of fossiliferous reefy limestone. This sequence locally unconformably overlies the Mitaki igneous rocks (Yasui, 1984) and the limestone includes granitic breccias (Yoshikura, 1982).

The melange matrix serpentinite is massive, brecciated, foliated or schistose and composed of lizardite, chrysotile, brucite, clinochlore, awaruite, pentlandite and magnetite. After the serpentinization of ultramafic protolith, it was subjected to greenschist- to amphibolite-facies metamorphism and formed antigorite, tremolite and new olivine and clinopyroxene. The principal protoliths of the serpentinite identified based on the relict minerals and pseudomorphic textures are dunite and harzburgite with lesser amount of lherzolite. These ultramafic protoliths are chemically and mineralogically more depleted than most ocean-ridge peridotite and are similar to subduction-related ultramafic rocks dredged from the Mariana and Tonga trenches (Yoshikura, 1988).

The late Permian accretionary complex is composed mainly of a chaotic muddy sequence and reefy limestone-basaltic greenstone complex (Isozaki, 1987). The chaotic muddy sequence is best described as mudstone-matrix melange and contains many allochthonous blocks of various lithologies, sizes and ages in block-in-matrix manner. The limestone-basaltic greenstone complex is considered to be a top portion of the accreted seamount.

The covering sediments that unconformably overlie the above-mentioned two geologic units are fairly well-bedded clastic sequences of terrigenous origin (Hada et al., 1992). They consist largely of coarse-grained sandstone and mudstone with intercalated conglomerates, and contain no exotic clasts of oceanic affinity. The Late Permian Doi Formation and Middle Jurassic Kagio Formation are typical examples of such sequences. The conglomerates are characterized by the occurrence of abundant clasts of granitic rocks with silicic volcanic and hypabyssal rocks which are assumed to have been derived from the Mitaki igneous rocks in the adjacent Kurosegawa Tectonic Zone (Kano, 1971; Yoshikura, 1982). The covering sediments were dated by radiolarian fossils (Hada et al., 1992), and these re-defined ages have been used in this paper.

TECTONIC EVOLUTION OF THE KUROSEGAWA TERRANE

Yoshikura et al. (1990) interpreted the tectonic evolution of the Kurosegawa Terrane as follows: the Mitaki igneous rocks and Terano metamorphic rocks were basement for the Siluro-Devonian sequence and they once formed a landmass of continental affinity referred to as “the Kurosegawa landmass”. Paleomagnetic data from the Siluro-Devonian sequence indicate that the landmass was situated far south of the present position of the Japanese Islands (at near paleoequatorial regions) in middle Paleozoic time (Shibuya et al., 1983). Faunal elements in the Early Silurian reefy limestones intercalated in the lower horizon of the Siluro-Devonian sequence are consistent with the paleomagnetic data indicating deposition at low latitudes, and are endemic to eastern Australia (Kobayashi and Hamada, 1974).

The late Paleozoic accretionary complex was formed at a convergent margin of the Kurosegawa landmass prior to collision with eastern margin of the Eurasian continent. The terrigenous Paleozoic and Mesozoic covering sediments were deposited in fore-arc and/or upper slope basins of the arc-trench system. Fusulinacean faunas of the Kurosegawa Terrane suggest that the Permian covering sediments originated from close to the eastern continental margin of the South China or Indochina/East Malaya blocks (Hada et al., 1996). The Kurosegawa landmass might be such a continental block. Paleomagnetic data plotted against time for the Kurosegawa Terrane indicates equatorial paleolatitudes from early Silurian to Jurassic and rapid northward travel during late Jurassic to early Cretaceous time (Sasajima and Maenaka, 1987). The landmass eventually collided with and accreted to the Eurasian continent by early Cretaceous time. This collision was oblique, and it disrupted and dispersed the Kurosegawa landmass into a narrow and elongate zone along the continental margin. This strike-slip faulting provided conduits for serpentinite protrusion to the surface, resulting in the formation of the serpentinite-matrix melange during earliest Cretaceous. Thus, the

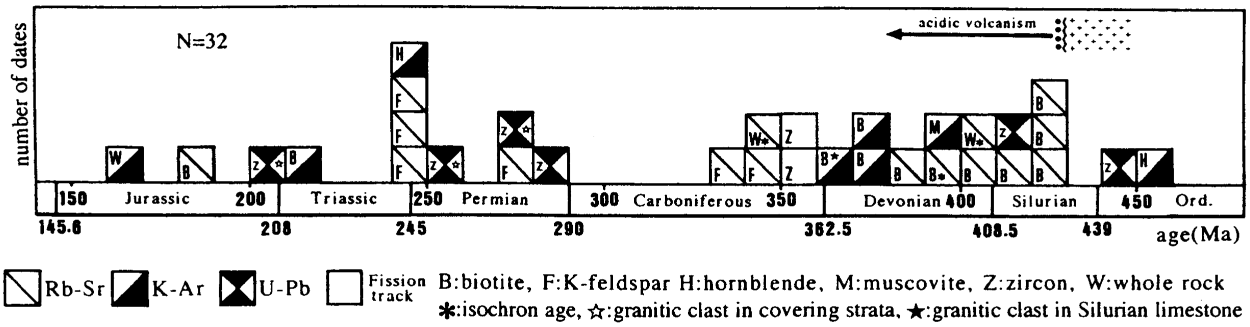

Fig. 2. Frequency distribution of isotopic ages for the Mitaki igneous rocks and granitic clasts in the Kurosegawa Terrane. The data sources are given in Yoshikura et al. (1981) and Yoshikura et al. (1990). All quoted K-Ar and Rb-Sr age are recalculated using the decay constants of Steiger and Jäger (1977).

Kurosegawa Terrane has been regarded as an exotic or far-traveled geologic entity with respect to its present position.

Recently, Isozaki and Itaya (1991) suggested that the overall distribution and structure of the Kurosegawa Terrane is controlled essentially by nappe structure and the terrane forms a sub-horizontal klippe thrust onto the post-Triassic accretionary complexes in the Outer Zone of Southwest Japan. They proposed an alternative model, on the basis of the lithologic similarity with the pre-Jurassic rocks in the Inner Zone, in which the Kurosegawa Terrane is a tectonic outlier detached from the Inner Zone. Murakami and Yoshikura (1992), however, suggested that the aeromagnetic anomaly observed in the Kurosegawa Terrane is not consistent with the thrusting veneer model, and is best explained by a model of a steeply north-dipping prism to depths of at least several kilometers. Thus, at the moment, the origin and tectonic evolution of the Kurosegawa Terrane is not yet fully understood and is still contentious.

GEOLOGIC CONSTRAINTS ON THE AGE OF THE MITAKI IGNEOUS ROCKS

The Mitaki igneous rocks are unconformably overlain by the Siluro-Devonian sequence consisting mainly of volcaniclastics interbedded with fossiliferous reefy limestones and terrigenous sediments low in the sequence. The age of the sequence given by fossil records ranges from late Llandoverian (ca. 430Ma, Early Silurian) (Kuwano, 1976) to Upper Devonian (Nikawa, 1986). The brecciated limestone contains pebble to cobble sized clasts of various lithologies, mainly granitic rocks resembling the Mitaki igneous rocks and lesser amounts of welded tuff and doleritic rocks. The terrigenous sediments are rich in lithic fragments and detritus derived from the granitic rocks. On the basis of this fossil and field evidence, it has long been considered that the Mitaki igneous rocks must necessarily be older than Early Silurian (cf. Yoshikura et al., 1990).

PREVIOUS DATING STUDIES AND PROBLEMS

The Mitaki igneous rocks have previously been dated by Rb-Sr, K-Ar and fission-track methods and their ages scatter widely from Ordovician to Jurassic (Fig. 2). However, it is obvious that there are two main clusters of the isotopic ages in the ranges 330 to 460Ma, and 160 to 290Ma, respectively. These clusters of dates can generally be interpreted in the following manner:

1) The older cluster may be interpreted as indicating the time of initial intrusion and crystallization of the Mitaki igneous rocks or, alternatively, it may reflect the age of thermal overprinting by Siluro-Devonian volcano-plutonic activity on pre-Early Silurian granites.
2) The younger cluster may be interpreted as indicating the original time of intrusion and crystallization of some of the Mitaki igneous rocks in a second period of igneous activity or, alternatively, as resetting the isotopic system of the older granitic rocks in response to tectono-thermal events during this period.

The scatter of dates in both clusters appears to be an excessively long time to be related to the post-magmatic cooling history in two periods of igneous activity. It could indicate either a protracted time period for the processes responsible for isotopic resetting, or variable magnitude of isotopic resetting for the individual samples. As previously mentioned, the Mitaki igneous rocks were deformed and metamorphosed under subgreenschist-facies conditions after crystallization. Hence, resetting of the K-Ar and Rb-Sr systems by the possible effects of subsequent tectono-thermal events can not be ruled out, although the metamorphism was not necessarily hot enough to reset the isotopic systems. In fact, granitic clast in the Early Silurian limestone gives a late Devonian biotite K-Ar age of 364±11Ma (Shibata et al, 1979). From the fossil age of the limestone, it is clear that the K-Ar biotite age of 364Ma for the granitic clast is not the age of crystallization but rather represents a later event that has reset the K-Ar system. More evidence of resetting of isotopic ages is that the two samples of the Mitaki igneous rocks give Rb-Sr whole rock isochron ages of 352±8Ma (Nohda, 1973) and 409±37Ma (Yanagi, 1975), but yield strongly discordant biotite K-Ar age of 209Ma (Kawano and Ueda, 1966) and whole rock K-Ar age of 163±13Ma (Shibata, 1968), respectively. The discrepancy between these isotopic ages can be explained by resetting of the K-Ar system during the Mesozoic. The K-Ar and Rb-Sr systems in the Mitaki igneous rocks may be partially or completely reset, so that the reported ages do not necessarily date a specific event.

Resolution of the age of the Mitaki igneous rocks requires confirmation by other geochronological metods. Premo et al. (1988) reported for the first time on an U-Pb zircon upper intercept age of 447±10Ma and a lower intercept age of 125±49Ma for the Mitaki igneous rock collected from an outcrop in the Mt. Yokokurayama area (Fig. 2) where the granitic rock has been unconformably overlain by the Siluro-Devonian sequence (Yasui, 1984).

U-Pb Geochronology: Analytical Techniques

Zircon was separated from ~25kg samples using conventional crushing, grinding, and Wilfley table techniques, followed by panning and hand-picking. Mineral fractions for analysis were selected based on grain morphology, quality, size and magnetic susceptibility. Except where noted in Table 1, all zircon fractions were abraded prior to dissolution to minimize the effects of post-crystallization lead-loss, using the technique of Krogh (1982). All geochemical separations and mass spectrometry were carried out in the Geochronology Laboratory at the University of British Columbia. Samples were dissolved in concentrated HF and HNO_3 in the presence of a mixed ^{233}U-^{235}U-^{205}Pb tracer. Separation and purification of Pb and U employed ion exchange column techniques modified slightly from those described by Parrish et al. (1987). Pb and U were eluted separately and loaded together on a single Re filament using a phosphoric acid-silica gel emitter. Isotopic ratios were measured using a modified single collector VG-54R thermal ionization mass spectrometer equipped with a Daly photomultiplier. Most measurements were done in peak-switching mode on the Daly detector. U and Pb analytical blanks were in the range of 1-6pg and 7-30pg, respectively, during the course of this study. U fractionation was determined directly on individual runs using the ^{233}U-^{235}U tracer. Pb isotopic ratios were corrected for a fractionation of 0.12%/amu and 0.43%/amu for Faraday and Daly runs, respectively, based on replicate analyses of the NBS-981 Pb standard and the values recommended by Todt et al. (1984). All analytical errors were numerically propagated through the entire age calculation using the technique of Roddick (1987). Analytical data are reported in Table 1, and interpreted ages are in Table 2. Concordia intercept ages and associated errors were calculated using a modified version of the York-II regression model (wherein the York-II errors are multiplied by the MSWD) and the algorithm of Ludwig (1980). Except where indicated, all errors are quoted at the 2σ level. Age assignments follow the time scale of Harland et al. (1990).

RESULTS

1. Mitaki igneous rocks

(1) GG-1 (Gyobuyabu, east of Mt. Torigatayama)

The granitic rocks at Gyobuyabu, Niyodo-mura, Kochi Prefecture (Figs. 1 and 3), which have previously been correlated with the Mitaki igneous rocks, were sampled for U-Pb dating. GG-1 is a medium-grained granodiorite and its modal mineralogy was given by Takagi et al. (1999).

Zircons separated from this rock are clear, colourless, euhedral doubly terminated prisms with aspect ratio 1:1-3 (the ratio of width to length of the crystals). No cores or inclusions are visible.

Four zircon fractions of differing magnetic susceptibilities and sizes have been analysed. All four fractions were air abraded. The analyses are plotted on the concordia diagram in Fig. 5a, and data are presented in Table 1. The four fractions lie on or near concordia in a configuration near the upper end of an isochron through zero with an intercept of 441.9±4.5Ma. Except for fraction (C), the zircons do not appear to contain inherited old zircon, but have suffered some minor lead loss. The position of fraction (C) on the plot is such that it might contain a small amount of inherited zircon of an age slightly older than the age of GG-1. If one fraction contained old zircon, then it is likely that all the zircon could have old cores. Assuming some inheritance in fraction (C), then a minimum limit for the age of this rock is given by the mean of the $^{206}Pb/^{238}U$ ages of the two oldest nearly concordant fractions, at 432.5±4.5Ma. The age obtained is consistent with a K-Ar date of 428±13Ma obtained from hornblende at the same locality (Sample No. 2701, Takagi et al., 1999).

The best estimate of the age of intrusion of this granite is 441.9±4.5Ma, and the rock is unlikely to be younger than 432.5±4.5Ma.

(2) TG-1A (Mt. Torigatayama area)

The granitic rocks at Ohue-ko, Niyodo-mura, Kochi Prefecture (Figs. 1 and 3), which have previously been correlated with the Mitaki igneous rocks, were sampled for U-Pb dating. TG-1A is a medium-grained to equigranular plagioclase-por-

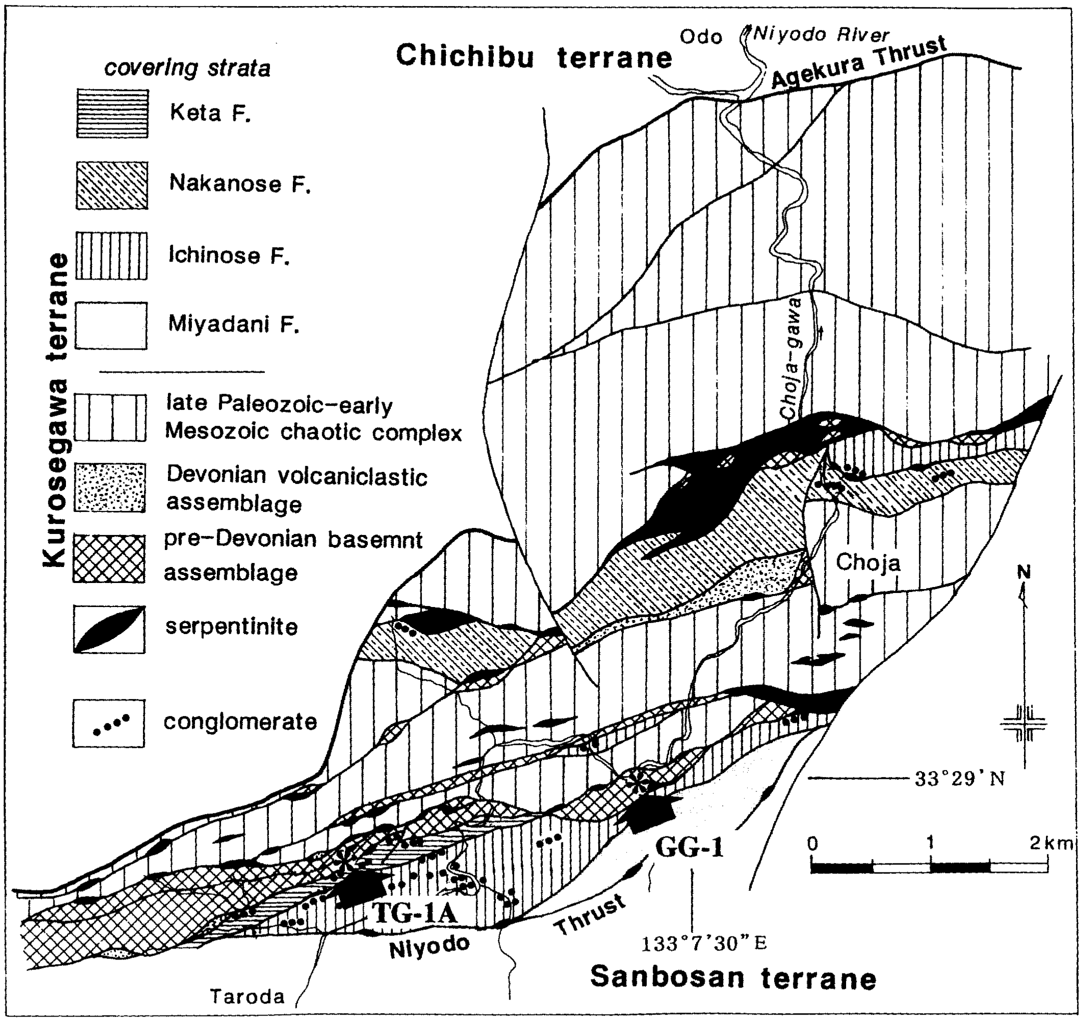

Fig. 3. Geologic map (after Hada et al., 1992) of the Kurosegawa Terrane in central Shikoku indicating the sample localities. Location of the map is indicated in Fig. 1.

phyritic granodiorite. It is composed mainly of plagioclase, quartz, K-feldspar and biotite. Apatite, zircon, and opaque minerals are accessory phases. They all tend to be present in association with biotite. Plagioclase is commonly altered to saussurite. Quartz shows strong undulatory extinction. Reddish brown biotite is kinked and shows undulatory extinction. Chlorite and sphene pseudomorphs after some prismatic crystal, probably hornblende, are present. Plagioclase and quartz are veined by calcite, chlorite and quartz along cracks which dislocate polysynthetic albite twins in plagioclases.

Zircons separated from this sample are very clear, colourless crystals. The population can be divided into two morphologies; acicular doubly terminated prisms with aspect ratios of 1:2-4, and multi-faceted lozenge-shaped crystals with aspect ratios of 1:1-2. No cores or zoning are visible, but some crystals contain clear fluid inclusions.

Three zircon fractions of differing morphologies, magnetic susceptibilities, and sizes have been analysed. All three fractions were air abraded. They lie on or near concordia (Fig. 5b), and a best-fit regression through zero provides an upper intercept age of 441.5±4.4Ma. There is minor lead loss from the zircon, and no component of inherited old zircon in this rock.

The U-Pb zircon age of 441.5±4.4Ma obtained for TG-1A is the same as the age obtained from GG-1, and also correlates well with the K-Ar biotite age of 434±13Ma obtained from the same sample (Sample No. 2702, Takagi et al., 1999). K-Ar ages tend to be slightly younger than U-Pb zircon ages even without a later thermal event, because of argon gas diffusion out of the rock. The fact that the U-Pb and K-Ar ages are similar suggests that the granite at this location has not undergone any thermal event such as high-grade metamorphism. This sample is a re-sampling of the assumed location of TG-1 to check the unexpected age (Hada and Yoshikura, 1991) compared to the age by Takagi et al. (1999) obtained for that sample. The two results show that the samples were not from the same rock (see the discussion on TG-1).

(3) MG-2 (Mt. Mitakiyama)

This sample was collected near the top of Mt.

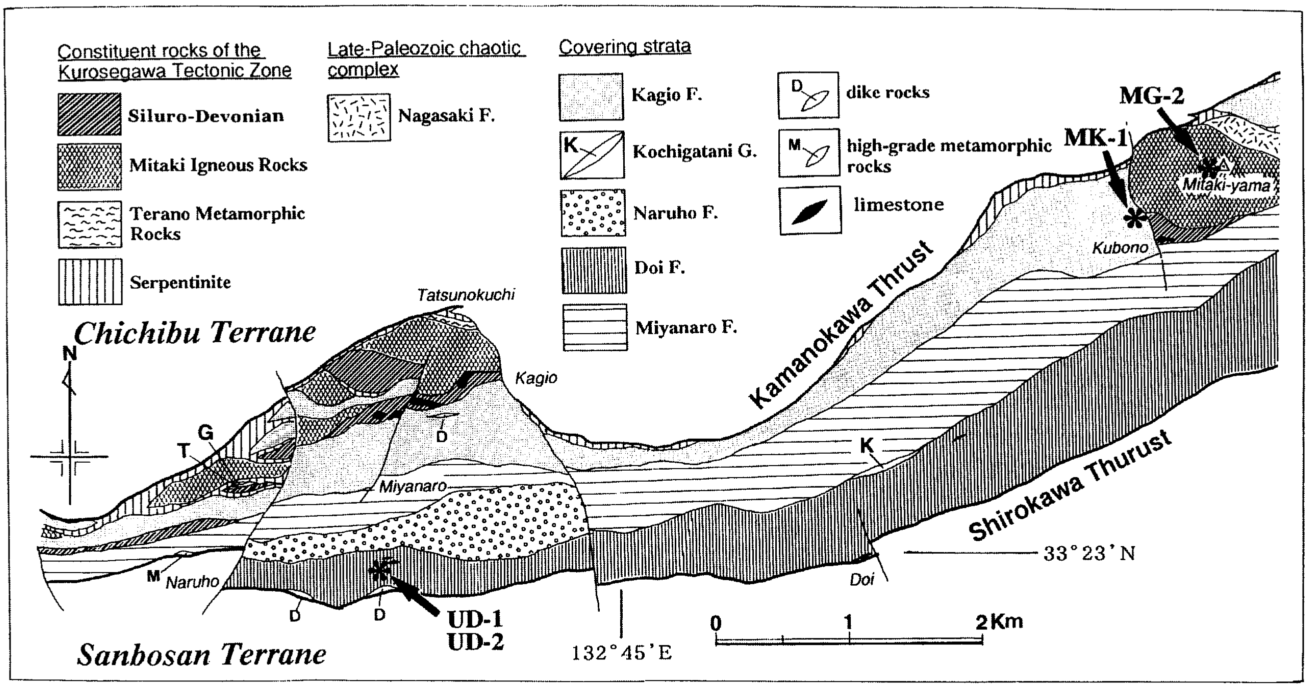

Fig. 4. Geologic map of the Kurosegawa Terrane in western Shikoku indicating the sample localities. Location of the map is indicated in Fig. 1.

Mitakiyama, Shirokawa-cho, Ehime Prefecture (Figs. 1 and 4) which is the type locality of the Mitaki igneous rocks (Ichikawa et al., 1956). MG-2 is a medium-grained granodiorite and consists essentially of plagioclase, quartz, K-feldspar and biotite. Accessory phases are apatite, zircon, allanite and opaque minerals. The plagioclase is quite extensively saussuritized but it is still identifiable as a plagioclase by polysynthetic albite twins. K-feldspar is fairly fresh and occurs as interstitial small grains. Biotite is totally altered to chlorite, prehnite, zoisite, epidote and sphene. Quartz shows some evidence of shearing such as undulatory extinction and deformation lamellae. In strongly sheared parts, fine aggregates of secondary quartz with sutured outlines are observed. Calcite, prehnite and quartz commonly occur as veins.

Zircons separated from this sample are clear, colourless to pale pink, euhedral short prisms with aspect ratio 1:2-3. They have no visible cores or inclusions. The coarser fractions contain 10% long, doubly terminated prisms which were not picked.

Two fractions were air abraded. The four data points (Table 1) define a best fit regression line yielding a late Ordovician upper intercept date of 439.7±10Ma (Fig. 5c and Table 2). Analysis of a non-abraded and abraded pair from the same size split ($-74+44\,\mu$m) (see the notes under Table 1) gives an indication of lead loss from zircons in this sample. The abraded fraction is nearly concordant, with a ^{206}Pb/^{238}U age of 425.2±1.0Ma. The non-abraded fraction is also nearly concordant, but at 370.2±1.5Ma, suggesting that the lead loss occurred at some time within 100Ma of intrusion. A fine, non-abraded fraction shows even more lead loss, and a slightly higher component of common lead than the other three fractions.

The array of fractions shows no evidence of the zircons containing inherited old zircon. The upper intercept date of 439.7±10Ma from a best-fit regression through the four fractions and zero is a good estimate of the age of intrusion of this granite, and is consistent with Ordovician dates obtained from other Mitaki igneous rocks in this study. From the results this rock cannot be older than 440.9±3.1Ma (^{207}Pb/^{206}Pb age of the most concordant fraction), and it confirms the U-Pb zircon date of 447±10Ma (Premo et al., 1988) for Mitaki igneous rocks in the Mt. Yokokurayama area. The U-Pb date is older than a Rb-Sr biotite date of 428±4Ma for the granitic rocks from this area (Hayase and Nohda, 1969), which can be considered a cooling or reset age, particularly as the biotite at this location has been altered.

2. Silurian-Devonian Sequence
TS-1 (Suberidani, Katsuura-cho, Tokushima)

This sample was collected from the Siluro-Devonian sequence within the Kurosegawa Terrane in the Suberidani area, Katsu-ura-cho, Tokushima Prefecture (Fig. 1). TS-1 is a vitric tuff just above a pinkish reefy limestone layer of a basal part of the sequence in the area.

The heavy concentrate from this sample of acidic tuff contained less than 0.1mg of zircon, which was split into two fractions. The zircons in the sample are clear, colourless to pale pink, broken pieces of

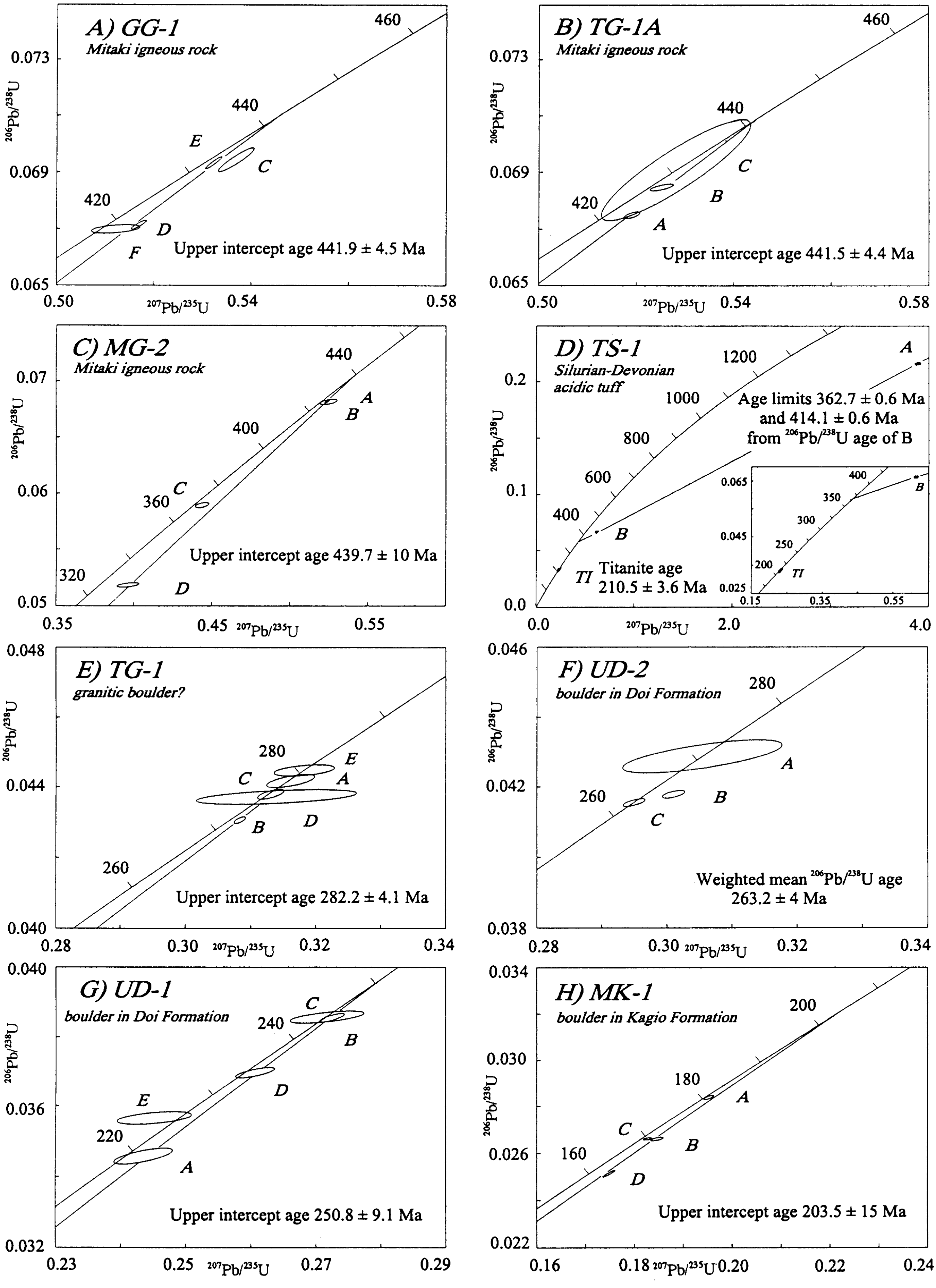

Fig. 5. Concordia diagrams showing U-Pb zircon results for samples from the Kurosegawa Terrane in Shikoku, Southwest Japan. Ellipses Indicate 2σ uncertainity.

Table 1. U-Pb analytical data for samples from the Kurosegawa Terrane, Southwest Japan.

Fraction[1]	Wt	U	Pb*[2]	^{206}Pb[3] / ^{204}Pb	Pb[4]	^{208}Pb[5]	Isotopic ratios (± 1σ %)[6] ^{206}Pb/^{238}U	^{207}Pb/^{235}U	^{207}Pb/^{206}Pb	Apparent ages (± 2σ, Ma)[6] ^{206}Pb/^{238}U	^{207}Pb/^{206}Pb
	mg	ppm	ppm		pg	%					
GG-1	**Granodiorite, Mitaki igneous rock**							**Gyobuyabu, Kochi**			
C M1 c	0.252	267	20	1447	204	17.2	0.06944 (0.31)	0.5369 (0.34)	0.05608 (0.12)	432.8 (7.7)	455.4 (5.5)
D M3 -c	0.496	289	21	3694	163	17.8	0.06714 (0.12)	0.5170 (0.15)	0.05585 (0.07)	418.9 (4.1)	446.3 (2.9)
E N1 -b	0.210	287	22	6770	39	16.8	0.06932 (0.16)	0.5322 (0.16)	0.05568 (0.05)	432.1 (2.6)	439.8 (2.1)
F M1 -d	0.095	170	13	553	123	17.2	0.06699 (0.11)	0.5122 (0.49)	0.05546 (0.45)	418.0 (2.5)	431 (20)
TG-1A	**Granodiorite, Mitaki igneous rock**							**Mt. Torigatayama, Kochi**			
A M1 -c, l	0.049	254	18	1136	47	15.4	0.06750 (0.09)	0.5191 (0.16)	0.05578 (0.12)	421.1 (0.7)	443.5 (5.2)
B N1 c, eq	0.081	202	15	848	84	16.0	0.06847 (0.09)	0.5252 (0.23)	0.05563 (0.18)	427.0 (0.7)	437.7 (8.0)
C M1 +c, l	0.076	174	13	520	110	15.7	0.06909 (1.3)	0.5281 (1.5)	0.05544 (0.65)	430.7 (11)	430 (29)
MG-2	**Granodiorite, Mitaki igneous rock**							**Mt. Mitakiyama, Ehime**			
A B +c	0.300	73	5	623	153	13.3	0.06816 (0.18)	0.5249 (0.53)	0.05585 (0.45)	425.1 (1.5)	447 (20)
B B -d+c	0.250	402	29	3556	121	13.9	0.06818 (0.12)	0.5238 (0.15)	0.05571 (0.07)	425.2 (1.0)	440.9 (3.1)
C B -c+d na	0.400	62	4	859	105	16.4	0.05911 (0.21)	0.4441 (0.50)	0.05449 (0.42)	370.2 (1.5)	392 (19)
D B -d na	0.100	64	4	216	102	17.6	0.05178 (0.25)	0.3944 (0.87)	0.05525 (0.72)	325.4 (1.6)	422 (33)
TS-1	**Silicic tuff, Siluro-Devonian sequence**							**Suberidani, Tokushima**			
T titanite	2.619	231	9	1566	822	22.0	0.03319 (0.87)	0.2323 (0.89)	0.05076 (0.15)	210.5 (3.6)	229.9 (6.7)
A N3 -c na	0.006	133	30	419	25	5.4	0.21618 (0.10)	3.8899 (0.26)	0.13050 (0.21)	1261.7 (2.3)	2104.7 (7.3)
B N3, p na	0.028	215	14	693	36	9.1	0.06635 (0.07)	0.6146 (0.30)	0.06718 (0.28)	414.1 (0.6)	843.4 (12)
TG-1	**Granitic boulder?**							**Location unknown**			
A B +a na	0.400	176	9	453	450	19.2	0.04418 (0.22)	0.3162 (0.59)	0.05191 (0.48)	278.7 (1.2)	281 (22)
B B -a+b	0.500	157	8	4757	45	20.6	0.04305 (0.11)	0.3083 (0.15)	0.05194 (0.10)	271.7 (0.6)	282.9 (4.7)
C B -b+c na	0.300	187	9	917	172	18.8	0.04380 (0.16)	0.3131 (0.33)	0.05185 (0.24)	276.3 (0.9)	278.9 (11)
D B -c+d	0.100	196	10	167	344	20.2	0.04372 (0.24)	0.3140 (2.0)	0.05209 (1.9)	275.8 (1.3)	289 (87)
E B –a+b na	0.300	187	9	456	341	19.0	0.04448 (0.18)	0.3183 (0.73)	0.05190 (0.67)	280.5 (1.0)	281 (31.0)
UD-2	**Quartz diorite boulder in Doi Formation**							**Shirokawa-cho, Ehime**			
A N1 -b+c	0.400	80	4	108	953	14.0	0.04288 (0.56)	0.3055 (2.0)	0.05167 (1.7)	270.7 (2.9)	271 (78)
B N1 -c+d	0.400	91	4	1051	94	13.7	0.04181 (0.15)	0.3032 (0.25)	0.05259 (0.19)	264.1 (0.8)	311.0 (8.6)
C M5 -c+d	0.150	189	8	668	114	13.0	0.04155 (0.13)	0.2950 (0.29)	0.05149 (0.22)	262.5 (1.1)	262.7 (10.1)
UD-1	**Quartz diorite boulder in Doi Formation**							**Shirokawa-cho, Ehime**			
A B -b+c na	0.800	274	10	256	2012	13.4	0.03458 (0.33)	0.2435 (0.93)	0.05108 (0.73)	219.1 (1.9)	245 (34)
B B -b+c	0.400	115	5	940	122	13.6	0.03855 (0.16)	0.2725 (0.36)	0.05127 (0.25)	243.9 (0.8)	252.9 (11)
C B -c+d, l na	0.200	134	5	224	313	13.8	0.03857 (0.22)	0.2717 (1.1)	0.05109 (0.92)	244.0 (1.1)	245 (43)
D B -c+d, eq na	0.400	292	11	437	650	13.1	0.03697 (0.20)	0.2607 (0.58)	0.05116 (0.44)	234.0 (0.9)	248 (21)
E B -d na	0.200	198	7	375	244	13.1	0.03565 (0.25)	0.2452 (1.2)	0.04989 (1.1)	225.8 (1.1)	190 (50)
MK-1	**Leucoc-granite boulder in Kagio Group**							**Mt. Mitakiyama, Ehime**			
A N1 c, eq	0.150	391	11	943	114	9.7	0.02838 (0.16)	0.1953 (0.27)	0.04990 (0.17)	180.4 (0.6)	190.5 (8.0)
B N1 -c+d na	0.100	865	23	563	267	9.0	0.02661 (0.14)	0.1847 (0.36)	0.05034 (0.28)	169.3 (0.5)	210.9 (13)
C N1 -d	0.100	1423	38	1163	207	9.0	0.02661 (0.09)	0.1827 (0.25)	0.04979 (0.20)	169.3 (0.3)	185.4 (9.5)
D N1 -d na	0.300	1954	49	1710	551	8.6	0.02514 (0.30)	0.1748 (0.37)	0.05043 (0.12)	160.0 (1.0)	215.0 (5.5)

Analyses by J.E. Gabites, 1989 to 1993.

IUGS conventional decay constants (Steiger and Jäger, 1977) are: $^{238}U\lambda=1.55125x10^{-10}a^{-1}$,
$^{235}U\lambda=9.8485x10^{-10}a^{-1}$, $^{238}U/^{235}U=137.88$ atom ratio.

Column one gives the label used in the concordia diagrams, Figures 3A-H.

[1] All fractions are air abraded except where indicated (na); Grain size, smallest dimension: a 149, b 104, c 74, d 44μm. mx = mixed sizes. Magnetic codes: Franz magnetic separator side-slope at which grains are nonmagnetic or magnetic, i.e. N1=nonmagnetic at 1°, M1=M1.8A/1°, M3 =M1.5A/3°, B = not split magnetically. Field strength for all fractions = 1.8A, except where M3 = 1.5A and M5 = 1A. Front slope for all fractions=20°. Grain character codes: l = elongate, eq = equant, p = prismatic, t = tabular, ti = tips.

[2] Radiogenic Pb

[3] Measured ratio corrected for spike and Pb fractionation of 0.0043/amu ± 20) (Daly collector)

[4] Total common Pb in analysis based on blank isotopic composition

[5] Radiogenic Pb

[6] Corrected for blank Pb, U and common Pb (Stacey-Kramers model Pb composition at the ^{207}Pb/^{206}Pb date of fraction, or age of sample).

Table 2. Interpreted ages of U-Pb zircon dates.

Sample Number	n	MSWD[2]	Lower concordia intercept (Ma ± 2σ)	Upper concordia intercept (Ma ± 2σ)	Interpreted Age (Ma ± 2σ)
GG-1	5[1]	8.32	0	441.9 ± 4.5	441.9 ± 4.5
TG-1A	4[1]	1.07	0	441.5 ± 4.4	441.5 ± 4.4
MG-2	5[1]	11.2	0	439.7 ± 10	439.7 ± 10
TG-1	5[1]	0.12	0	282.2 ± 4.1	282.2 ± 4.1
UD-2	3		263.2 ± 0.2[3]		263.2 ± 0.2[3], with minor inheritance
UD-1	5[1]	0.14	0	250.8 ± 9.1	250.8 ± 9.1
TS-1	2	0.00	362.7 ± 1.7		Between 362.7 ± 1.7 &414 ± 0.6[3] with inheritance;
	1		210.5 ± 3.6[4]		metamorphism 210.5 ± 3.64
MK-1	51	14.63	0	204 ± 15	204 ± 15

1. Calculation of least squares regression after Ludwig (1980) forced through zero, n includes zero point.
2. MSWD = mean square weighted deviance
3. Weighted mean of ^{206}Pb/^{238}U ages.
4. ^{206}Pb/^{238}U age of titanite.

prisms. No cores or zoning were visible, but most were fractured. The pieces broke into small shards during abrasion. A titanite separate was also analysed. The titanite consists of large, pale yellow, faceted irregular-shaped crystals.

The rock is unique within the suite of rocks that we have dated, as it is the only one that clearly contains inherited old zircon. Both zircon fractions contain significant inherited components (Fig. 5d), but also might have undergone a complex history including lead loss. Unfortunately neither fraction was abraded to remove material which might have suffered post-crystallization lead loss. The rock is a tuff, which might contain old detrital zircons from some unknown source. A best-fit regression through the two zircon fractions provides a lower intercept age of 362.7±1.7Ma, which could be considered a minimum age for crystallization of the tuff. The ^{206}Pb/^{238}U age of 414.1±0.6Ma of the most concordant zircon fraction (B) can be considered an upper limit. The titanite analysis is nearly concordant with a ^{206}Pb/^{238}U age of 210.5±3.6Ma (Table 1 and Fig. 5d). Titanite is almost never primary in volcanic rocks, therefore the date represents a metamorphic event at 210.5±3.6Ma.

Age constraints on this rock are poor, but the best estimate is that the tuff crystallized between 362.7±1.7Ma and 414.1±0.6Ma ago, and was metamorphosed at 210.5±3.6Ma. U-Pb SHRIMP ages on similar tuffs in nearby areas of 427±7.6Ma and 408.9±7.6Ma (Aitchison et al., 1996) strengthens the interpretation of our data.

3. Granitic boulder?

TG-1

Zircons separated from this sample are clear, colourless to light amber, euhedral long doubly terminated prisms. Most (80-90%) of the crystals are broken, but no cores are visible. Two fractions were air abraded.

The five fractions analysed (Table 1) cluster on concordia near 280Ma (Fig. 5e), indicating an early Permian date. There is no evidence for inheritance of old zircon in this rock. Minor lead loss is apparent in the coarse fraction, with the abraded split plotting slightly below concordia and younger than the other points. However, abrasion of the coarse fraction did not change significantly either the U and Pb concentrations or the dates obtained from that fraction. The best estimate of the age of this rock has been taken from the upper intercept of a modified York (1969) regression through zero, which is equivalent to the weighted mean of the ^{207}Pb/^{206}Pb dates. This date is 282.2±4.1Ma, which may be interpreted confidently as reflecting the magmatic crystallisation age of this rock.

After the Permian age was obtained on TG-1 (Hada and Yoshikura, 1991), the locality (Ohue-ko, Mt. Torigatayama; Fig. 3) was re-sampled and a K-Ar biotite age of 434±13Ma was obtained (Takagi et al., 1999). The zircon date discussed above (TG-1A) was obtained on the same second sample. Both zircon dates are of good quality and is not possible to interpret either of them as related to the other. The zircons from the two samples are different in morphology and general appearance. We now consider that the zircon concentrate from TG-1 was mis-labelled and is actually from a different sample, which was a granite clast in a conglomerate. Despite the confusion in the origin of the sample from which the date of 282.2±4.1Ma was obtained, we have chosen to report it here, as it does indicate the presence of Permian granitic rocks in the Kurosegawa Terrane.

4. Granitic boulder

(1) UD-2 (Upper Permian Doi Formation)

The Doi Formation mainly consists of sandstone, conglomerate and mudstone, with subordinate silicic tuff and small lenses of limestone. UD-2 is collected from an intraformational conglomerate bed just below the *Lepidolina*-bearing limestone bed and the black mudstone yielding Late Permian radiolarians at the outcrop along the Kurosegawa River, Shirokawa-cho, Ehime Prefecture (Figs. 1 and 4).

UD-2 is a medium-grained equigranular quartzdiorite and consists chiefly of plagioclase, quartz and small amount of K-feldspar. Accessory phases are zircon, apatite and opaque minerals. Plagioclase poikilitically includes tiny crystals of hornblende and is intensely altered to saussurite. Mafic clots consisting of fine biotite are observed. Epidote, prehnite and chlorite are alteration products of biotite. Pleochroism of the hornblende changes from pale green to yellowish green. In strongly sheared parts, microveinlets consisting mainly of recrystallized quartz and feldspars are present. Calcite, prehnite and quartz veins cut all main constituent phases.

Zircons from this sample are clear, colourless to pale pink, and a mixture of short and long prismatic euhedral to subhedral crystals. Aspect ratios are 1:1-2 and 1:3-6. Many of the coarser crystals contain fluid inclusions, and rare cloudy cores were avoided. All three fractions were air abraded.

The three fractions reported all plot close to concordia, one with large errors (Fig. 5f). In general, a rock cannot be older than the youngest concordant fraction. This limit is 262.5±1.1Ma, given by the $^{206}Pb/^{238}U$ age of fraction (C). The position of fraction (B) on the plot suggests that the granite may contain inherited old zircon, although the zircons in this fraction might also have undergone lead loss, which would move it off concordia. A conservative estimate of the age of the rock is 263.2±4Ma, the weighted mean of fractions (B) and (C). The error is slightly expanded taking into account the possibility of lead loss and inheritance.

As with sample UD-1, this rock is a boulder in a conglomerate, thus it has undergone a complex history involving at least one erosional cycle. Our interpretation of U-Pb analysis of this granite boulder is that it has undergone a complex isotopic history, and that the age of crystallization is 263.2±4Ma. This rock is the only granite dated in this study which shows evidence of possible inherited old zircon.

(2) UD-1 (Upper Permian Doi Formation)

UD-1 was collected from the same conglomerate bed with UD-2 at the same locality (Figs. 1 and 4).

UD-1 is a coarse-grained and equigranular quartzdiorite. This rock is composed essentially of plagioclase and quartz. Other mineral constituents include K-feldspar, biotite, hornblende, accessory zircon, apatite, sphene and opaque minerals. Plagioclase exhibits a high degree of alteration to saussurite. Shearing effects are indicated by bending of plagioclase and by undulatory extinction of quartz and feldspars. Quartz is commonly recrystallized to fine aggregates of secondary quartz with sutured outlines. Most biotites are interleaved with prehnite. Hornblende is pleochroic from pale green to brownish green. UD-1 is veined by calcite, quartz, albite, chlorite, and epidote.

Zircons recovered from this sample are clear, colourless to pale tan, short euhedral prisms. There are approximately 15% long doubly terminated prisms in the $-74+44\mu$m fraction; these were analysed separately. Some small dark inclusions are contained in the coarser crystals, but no cores are visible. One fraction was air abraded.

The five fractions plot as points with 2σ error envelopes overlapping concordia between 220 and 250Ma. We interpret the array of points as showing lead loss from the zircons. An abraded fraction (B in Fig. 5g) has a $^{206}Pb/^{238}U$ age of 243.9±0.8Ma, while an unabraded fraction (A) of the same size split has a $^{206}Pb/^{238}U$ age of 219.1±1.9Ma. We have used an assumed lower intercept of zero to calculate the best-fit regression yielding an upper intercept age of 250.8±9.1Ma (Fig. 5g). The date obtained is Late Permian, which is the stratigraphic age of the conglomerate containing the boulder. The granite has gone through at least one cycle of cooling, uplift and erosion, so the pattern of lead loss and isotopic disturbance could be quite complex.

(3) MK-1 (Middle Jurassic Kagio Formation)

The Kagio Formation is divided into lower sandstone-rich and upper mudstone-rich members. MK-1 was collected from the conglomerate layer which occurs in the lower member of the Mt. Mitakiyama area, Shirokawa-cho, Ehime Prefecture (Figs. 1 and 4). MK-1 is a coarse-grained leucocratic granite. Principal minerals are K-feldspar, quartz and plagioclase with small amount of biotite. Accessory phases are zircon, allanite, apatite and opaque minerals. K-feldspar is perthitic with coarse patchy sodic lamellae. Plagioclase is rimmed by a thin zone of clear albite. Quartz shows undulatory extinction and deformation lamellae. Biotite is brown and commonly altered to chlorite.

Zircons separated from this sample are clear, amber coloured euhedral crystals. They are a mixture of short and long double terminated prisms, and most of the coarser crystals are broken pieces. The long prismatic crystals have some fluid inclusions, but cores are not apparent.

The four fractions analysed produce a collinear array (Fig. 5h), and define an upper intercept age of 203.5±15Ma for a best fit least squares regression through zero. The lead loss pattern is simple, and there is no indication of inheritance of old zircon. Thus 203.5±15Ma, which is early Jurassic, is a minimum age for the magmatic crystallisation of the boulder protoliths in this conglomerate in the Kagio Formation.

DISCUSSION

1. Age of the Mitaki igneous rocks

The U-Pb zircon ages for the three *in situ* granites from the Mitaki igneous rocks reported herein are very close in age: 441.9±4.5Ma for GG-1, 441.5±4.4Ma for TG-1A, and 439.7±10Ma from MG-2. The lead systematics for these three samples are very similar, and although all have undergone post-crystallisation lead loss, none appear to contain any significant component of inherited old zircon. This reflects the lack of older crust, or rocks derived from older crust, in the area where the granite magma was generated. The granitic rocks at the three locations sampled appear to be closely related in age and magmatic origins. GG-1 and TG-1A are located only a few kilometres away from each other, and are likely to be samples from the same body. The three ages plot at the older end of the older cluster of previously reported ages for granitic rocks (Fig. 2).

As discussed above, the Mitaki igneous rocks must pre-date the overlying Siluro-Devonian sequence, of which a lower horizon contains Llandoverian (ca. 430Ma) fossils (Kuwano, 1976). However, only 2 of 32 previous dates are older than 430Ma (Fig. 2). The dating methods used for most of these analyses are susceptible to resetting by subsequent geological events such as burial, metamorphism and uplift. They must therefore be considered as minimum ages of intrusion, or metamorphism. In contrast, zircon U-Pb ages are not readily reset, and tend to indicate the time of intrusion of granitic rocks.

The oldest late Ordovician date (450±12Ma) so far obtained was a hornblende K-Ar date from granitic rocks in the Mt. Gionyama area in Kyushu which are considered correlatives of the Mitaki igneous rocks (Umeda et al., 1986). Considering that the hornblende is only weakly altered, this date appeared to indicate a cooling age and records the time at which the granitic rock cooled to the blocking temperature of hornblende (approximately 535℃; Harrison, 1981). This age and the U-Pb zircon dates of this study and Premo et al. (1988) suggest that the oldest igneous activity occurred at about 440 to 450Ma.

Most of the previously recorded dates on granitic rocks in the older cluster (Fig. 2) and high-grade metamorphic rocks are younger than the stratigraphic age of the overlying strata, and appear to be reset during the middle Silurian to early Carboniferous. One possibility is that the metamorphism and resetting of isotopic systematics could have been caused by heating from Siluro-Devonian magmatism; however, evidence of a widespread episode of magmatism during this time is weak. The date reported here for Sample TS-1 is the first U-Pb zircon date recorded in the 350-400Ma age range. Another option is that later low-grade metamorphism reset the Rb-Sr and K-Ar systems. Evans (1991) suggested that under even low-grade metamorphic conditions such as prehnite-pumpellyite-facies, Rb-Sr whole rock ages could be totally reset if water is present.

2. Siluro-Devonian sequence

TS-1 is a sample of a silicic tuff collected from the Siluro-Devonian sequence in the Kurosegawa Terrane. Very little zircon was available to analyse, and the isotopic systematics are disturbed. The analysis suggests that the rock was erupted between 362.7±1.7Ma and 414.1±0.6Ma ago, with inherited old zircon and lead loss, and was metamorphosed at 210.5±3.6Ma. The inherited component indicates that either the magmatic source was quite different from that of both the Mitaki igneous rocks and the Permian granites represented in the conglomerates, or that old detrital zircon was incorporated into the tuff during sedimentation. A titanite analysed from this rock indicates a Mesozoic metamorphic event.

3. Geological implications of the granitic boulders

The U-Pb zircon dates of the granitic clasts reported in this study provide constraints on the maximum age of sedimentation of the host conglomerates as well as on the age distribution in the source areas. The deposition of the conglomerates in the Doi and Kagio Formations must post-date the youngest clasts that they contain. Permian ages of 263.2±4Ma (UD-2) and 250.8±9.1Ma (UD-1) obtained from clasts in the Doi Formation and an early Jurassic age of 203.5±15Ma (MK-1) from the Kagio Formation both fall the range of sedimentary ages based on radiolaria (Hada et al., 1992) within these strata. This indicates rapid uplift and erosion soon after emplacement of the boulder protolith, and rapid transport and deposition. Both the Doi and Kagio Formations are often intercalated with silisic tuff layers. The granitic clasts in these formations are also closely associated with clasts of silicic volcanic and hypabyssal rocks and seem to have been derived from shallow granitic intrusions related to silicic volcanism which occurred in a magmatic arc setting. Geochemistry of the granitic clasts supports a magmatic arc setting (our study in progress; Hada, 1990). It is highly probable that these shallow granitic intrusions were uplifted and eroded within a few million years of emplacement, as recognised in other areas in studies by Graham and Korsch (1990), Asmerom et al., (1990), and Kimbrough et al., (1992).

Our U-Pb dates show that the Ordovician Mitaki igneous rocks are unlikely to be the protolith for the granitic clasts in the conglomerates. Our sampling was small, only three or four clasts were dated, but they were chosen because they were petrographically similar to the Mitaki igneous rocks. This suggests that the Mitaki igneous rocks were not exposed where Permian to Jurassic sedimentation was occurring. We surmise that the protolith for the Permian granitic clasts in the Permian conglomerate was a magmatic arc located not far from the site of deposition of those conglomerates. The palaeomagnetic and palaeontologic (fusulinasean faunas) evidence (Shibuya et al., 1983; Hada et al., 1996) indicates that the magmatic arc might be situated in the continental margin of the South China or Indochina/East Malaya continental blocks. As mentioned earlier, "the Kurosegawa landmass" is considered to be such a continental block.

Recently, Takagi and Shibata (1996) and Takagi et al. (1997) suggested that the nappes on the Mikabu greenstones in Kanto Range, western Shikoku, and eastern Kyushu were remains of allochthonous bodies once interleaved tectonically between the Ryoke metamorphic belt on the north of the Median Tectonic Line and the Sambagawa Terrane (Fig. 1). The Mikabu greenstone itself tectonically overlies the Sambagawa metamorphic rocks. Those nappes are composed of Permian granitoid, Early Cretaceous High-grade metamorphic rocks and Late Cretaceous terrigenous sediments (Takagi and Fujimori, 1989; Takagi et al., 1989; Takeda, 1995). Takagi and Shibata (1996) and Takagi et al. (1997) regarded those as the correlative to the South Kitakami and Abukuma Terranes in Northeast Japan. The Permian granitoids of those nappes were dated between 247 to 277Ma by K-Ar on hornblende and 252 to 275Ma by Rb-Sr whole-rock isochron ages. The ages and initial $^{87}Sr/^{86}Sr$ ratios of the granitoids indicate that Permian granitoids are protolith to the granitic clasts in the Usuginu conglomerate in the South Kitakami Terrane of Northeast Japan (Shibata and Takagi, 1989; Takagi and Shibata, 1996). The Permian conglomerates bearing abundant clasts of granitic rocks in the Kurosegawa Terrane, including those of the Doi Formation, have been correlated to the Usuginu conglomerate in the Outer Zone of Southwest Japan (Kano, 1971).

On the other hand, Takeda et al. (1993) recognised that such nappes on the Mikabu greenstone in west Shikoku are also composed of the Jurassic accretionary complex and were formed during Palaeogene. Hada and Kurimoto (1990) showed the existence of a nappe consisting of Jurassic accretionary complex (Nakatsuyama nappe) that tectonically overlies the Mikabu greenstone, the Chichibu Terrane, and also the Kurosegawa Terrane.

The correlation of rocks and nappes mentioned above suggests that the protolith for the Permian granitic clasts in the Permian conglomerate in the Kurosegawa Terrane and the Usuginu conglomerate in the South Kitakami Terrane was a magmatic arc located possibly in the South China or Indochina/East Malaya continental blocks. At that time the Mitaki igneous rocks were not exposed where the Permian sedimentation was proceeding. Then the Asian continent was formed by the juxtaposition of a number of such continental blocks during the Triassic (e.g. Metcalfe, 1996; Hada et al., 1999). The Jurassic accretionary complex and Jurassic granitic clasts bearing conglomerates are inferred to have formed in the eastern peripheral zone of the continent by the process of plate subduction. It is highly probable that the continental region and collage zone of the Asian continent were transpressed, dispersed, and displaced along the margin up to the north (Mizutani and Yao, 1991). This caused not only the migration of various continental rocks and the accretionary complex to Northeast Japan (South and North Kitakami, and Abukuma Terranes) by way of the present position of the Median Tectonic Line but also the formation of a nappe structure onto the Sambagawa, Mikabu, and Chichibu rocks in Paleogene.

In contrast, the above-mentioned nappes bearing the Jurassic accretionary complex tectonically overlie the Kurosegawa Terrane situated between the Chichibu and Sanbosan Terranes in Shikoku (Hada and Kurimoto, 1990; Takeda et al., 1993). It means that the emplacement of the Kurosegawa Terrane into the present position must be earlier than the emplacement of the nappes. Accordingly, the Mitaki igneous rocks are inferred to have originated as the Ordovician crystalline basement of the South China or Indochina/East Malaya continental blocks that were rifted from the Gondwanaland by the Late Devonian (Hada et al., 1999). The Siluro-Devonian sequence, the late Paleozoic accretionary complex and the terrigenous Paleozoic covering sediments were formed in the continental margin of the block under the tectonic framework of the magmatic arc situation. After the amalgamation of such continental blocks to the Asian continent as explained above, the continental region and its collage zone were sliced and fragmented at the latest in earliest Cretaceous time by the strike-slip movement, in a process similar to that described above but at an earlier time. As a result, the Kurosegawa Terrane was formed as a terrane characterized by the serpentinite melange zone between the Chichibu and Sanbosan Terranes.

CONCLUSIONS

In summary, previous views concerning the age of the Mitaki igneous rocks, Siluro-Devonian sequence and granitic boulders from the Permian and Jurassic strata in the Kurosegawa Terrane and their geological implications are changed by the data presented above.

(1) Three Mitaki igneous rocks yielded U-Pb dates of 441.9±4.5Ma, 441.59±4.4Ma and 439.7±10Ma, respectively. These results and paleomagnetic and paleontologic evidences suggest that the Mitaki igneous rocks were generated in the late Ordovician time as a crystalline basement of the South China or Indochina/East Malaya continental blocks.

(2) The Siluro-Devonian vitric tuff is dated between 362.7±41.7Ma and 414.1±0.6Ma. The inherited component of a silicic tuff collected from the Siluro-Devonian sequence indicates that either the magmatic source was quite different from that both the Mitaki igneous rocks and the Permian granites represented in the conglomerates, or that old detrital zircon was incorporated into the tuff during the sedimentation.

(3) Permian U-Pb zircon ages of 263.2±4Ma and 250.8±9.1Ma were obtained for the granitic boulders from the Permian Doi Formation, and a Jurassic age of 203.5±15Ma for the granitic boulder from the Jurassic Kagio Formation. This shows that the protolith for the granitic clasts in the conglomerates is not the Mitaki igneous rocks but was a magmatic arc located possibly in the continental margin of the South China or Indochina/East Malaya continental blocks.

(4) These ages of the granitic boulders fall within the range of sedimentary ages for the conglomerates. This indicates that rapid uplift and erosion soon after emplacement of the boulder protoliths, and rapid transport and deposition of the conglomerates.

(5) The present study in conjunction with previous studies provide several lines of evidence that the Permian to Triassic granitoids were once widespread in the parental continent forming a magmatic arc with felsic volcanic and hypabyssal rocks.

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（要　旨）

Hada, S., Yoshikura, S. and Gabites, J. E., 2000, U-Pb zircon ages for the Mitaki igneous rocks, Siluro-Devonian tuff, and granitic boulders in the Kurosegawa Terrane, Southwest Japan. *Mem. Geol. Soc. Japan*, no. 56, 183-198. （波田重熙・吉倉紳一・ギャヴィティーズ，J.E.，2000，西南日本黒瀬川テレーンの三滝火成岩類，シルル・デボン系凝灰岩，および，花崗岩礫に含まれるジルコンのU-Pb年代．地質学論集，第56号，183-198.）

黒瀬川地帯の三滝火成岩類，シルル-デボン系酸性凝灰岩，土居層と嘉義尾層の花崗岩礫について，U-Pb法によるジルコンの年代測定を行った．三滝火成岩類については439～441Ma，また，シルル-デボン系については362～414Maの年代が得られた．花崗岩礫については263Maおよび250Ma（土居層），203Ma（嘉義尾層）の年代が得られた．これらは，各々の地層の堆積年代に近いことから，礫の供給源となった花崗岩は貫入定置後，急速に上昇・削剥・供給されたとみられる．また，これらの礫の年代は三滝火成岩類のそれより明らかに若いので，供給源を三滝火成岩類に求めることはできない．供給源は，南中国あるいはインドシナ／東マレーシア大陸地塊，および，それらが衝突・合体して形成されたアジア大陸の大陸縁辺域に位置していた火成弧と見なされる．一方三滝火成岩類は，上記の大陸地塊がゴンドワナ大陸から分裂・移動する以前の結晶質基盤岩類と考えられる．