

A >1,000-km-long mid-Cretaceous low-pressure/high-temperature plutono-metamorphic system along the East Asian margin

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Abstract Recent K–Ar ages from the Abukuma Metamorphic Rocks in the Gosaisho–Takanuki area provide a chronological anchor for re-evaluating mid-Cretaceous low-P/T metamorphism and plutonism along the East Asian margin. The Gosaisho–Takanuki, Takato–Shiojiri, Iwakuni–Yanai, and Higo areas record broadly coeval low-P/T metamorphism and Cretaceous plutonism and collectively define a margin-scale plutono-metamorphic system. We propose a testable geodynamic model in which slab rollback, or a related change in subduction geometry, promoted asthenospheric upwelling and mantle-wedge heating, increased slab-derived fluid and melt fluxes, and ultimately contributed to distinctive magmatism, granitoid generation, and regional low-P/T metamorphism. Magmatic features potentially related to rollback are particularly well documented in SW Japan, including high-Nb basaltic magmas, adakites, high-Mg andesites, and evidence for slab-derived components in Cretaceous granitoids. Further evaluation of this hypothesis requires integrated petrological, geochronological, and geochemical datasets from less well-studied segments of the proposed system. In particular, establishing links among mafic to intermediate magmatism, granitoid generation, and regional low-P/T metamorphism is essential for evaluating the scale and mechanism of this tectono-thermal system.

Keywords : Abukuma Metamorphic Rocks, low-P/T metamorphism, mid-Cretaceous plutonism, slab rollback, subduction geometry

1. Introduction

Since Miyashiro's (1961) paired metamorphic-belt concept became widely accepted, the Abukuma Metamorphic Rocks of NE Japan have been regarded as a classic andalusite–sillimanite-type, low-pressure/high-temperature (low-P/T) regional metamorphic unit associated with Cretaceous granitic plutons. Recent K–Ar dating of muscovite and biotite from the Gosaisho and Takanuki units, which comprise contrasting oceanic and terrigenous lithologies within the Abukuma Metamorphic Rocks, yielded broadly similar ages of ca. 100 Ma, suggesting that they shared a common mid-Cretaceous thermal history after their tectonic juxtaposition (Itaya, 2025). Recent monazite geochronology further indicates that metamorphic rocks from different lithotectonic units and crustal levels of the Abukuma Mountains record a regionally coherent thermal event at ca. 115–104 Ma, broadly overlapping with Cretaceous granitoid

magmatism (Suwa and Tsunogae, 2026). These results are broadly consistent with K–Ar and U–Pb constraints on Cretaceous plutonism and rapid cooling in the southern Abukuma Mountains (Shibata and Uchiumi, 1983; Takahashi *et al.*, 2016; Wang *et al.*, 2023).

Comparable low-P/T metamorphic domains associated with Cretaceous plutonism occur in the Takato–Shiojiri, the Iwakuni–Yanai, and the Higo areas (e.g., Ono, 1977; Nakajima, 1994; Nagakawa *et al.*, 1997; Ikeda, 2004) (Fig. 1; Table 1). In pelitic rocks, these low-P/T metamorphic domains are characterized by progressive changes in mineral assemblages from low-grade biotite + chlorite assemblages, through andalusite-bearing assemblages, to higher-grade assemblages such as garnet + cordierite, sillimanite + K-feldspar, and K-feldspar + cordierite (Fig. 2). The higher-grade zones are locally associated with migmatites and textural evidence for partial melting, consistent with repeated magmatic heat input and crustal anatexis during the

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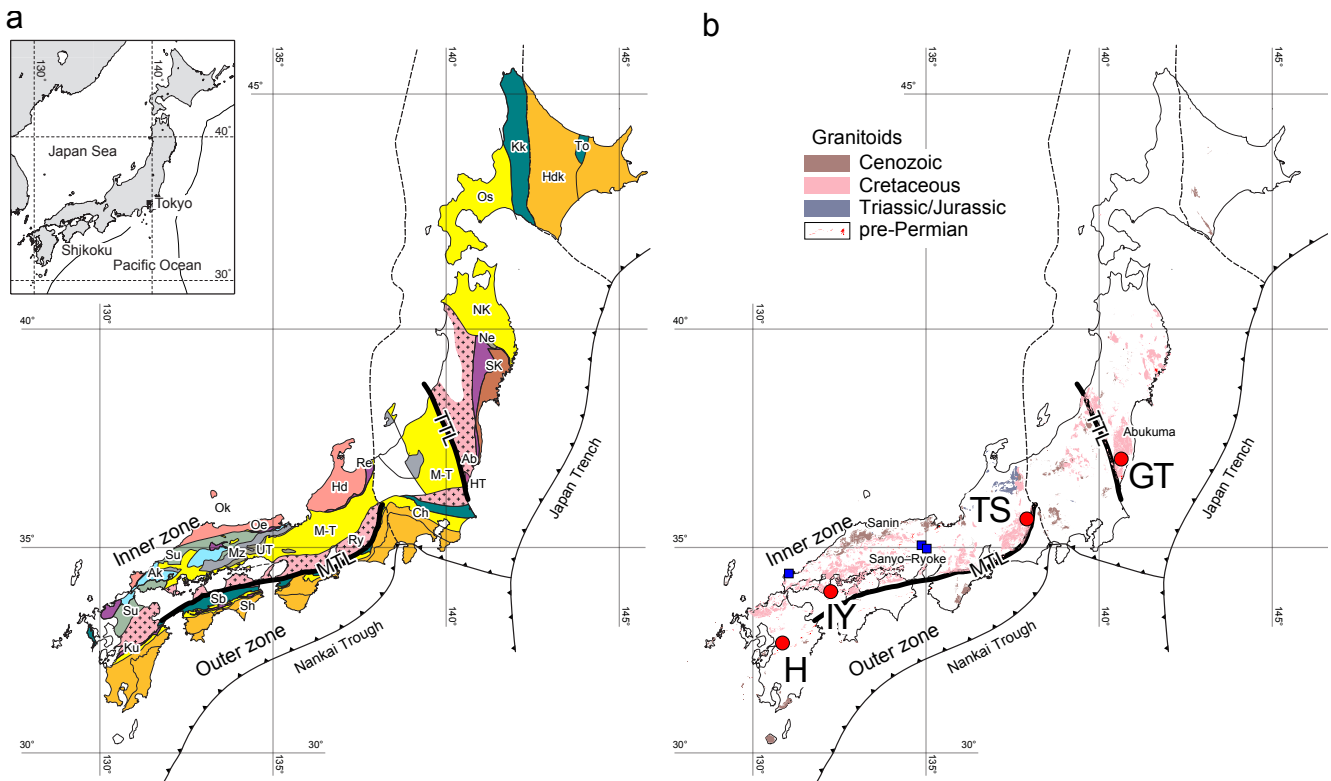


Fig. 1 (a) Geotectonic subdivision of pre-Paleogene basement rocks in major areas of the Japanese Islands, modified after Isozaki and Maruyama (1991), Tsujimori and Itaya (1999), Pastor-Galán *et al.* (2021), and Tsujimori *et al.* (2024). The map was drawn using the Mercator projection. MTL, Median Tectonic Line; TTL, Tanakura Tectonic Line. Geotectonic unit abbreviations: Ab, Abukuma; Ak, Akiyoshi; Ch, Chichibu; Hd, Hida; Hdk, Hidaka; HT, Hitachi; Kk, Kamuikotan; Ku, Kurosegawa; M-T, Mino-Tamba; Mz, Maizuru; Ne, Nedamo; NK, Northern Kitakami; Oe, Oeyama; Ok, Oki; Os, Oshima; Re, Renge; Ry, Ryoke; Sb, Sambagawa; SK, Southern Kitakami; Sh, Shimanto; Su, Suo; To, Tokoro; UT, Ultra-Tamba. (b) Distribution of granitoid rocks and major batholith belts in the main Japanese Islands, including the Sanin, Sanyo-Ryoke, and Abukuma belts, with filled red circles indicating the locations of the Gosaisho-Takanuki area (GT), Takato-Shiojiri area (TS), Iwakuni-Yanai area (IY), and Higo area (H). Filled blue squares indicate mid-Cretaceous volcanic rocks in SW Japan that may provide evidence for slab rollback-related magmatism; see text for details. Data are from the Seamless Digital Geological Map of Japan v2, 1:200,000, Geological Survey of Japan, AIST (2023).

Cretaceous plutonism (e.g., Okudaira *et al.*, 2024). Available geochronological data indicate that metamorphism and plutonism in these areas broadly overlapped at ca. 110–95 Ma. Together, these areas define an along-margin low-P/T plutono-metamorphic system extending for more than 1,000 km along the East Asian continental margin (Fig. 1).

A key unresolved problem is whether this margin-scale system can be explained by local pluton heating alone, or whether it required a broader tectono-thermal process. Previous studies have suggested that slab rollback, or comparable changes in subduction geometry, generated transient thermal and magmatic anomalies in SW Japan during the mid-Cretaceous (Kiminami and Imaoka, 2013; Imaoka *et al.*, 2014, 2017; Suga and Yeh, 2020). Using the Gosaisho-Takanuki K–Ar framework as a starting point, we propose a testable geodynamic model for this >1,000-km-long mid-Cretaceous low-P/T plutono-metamorphic system. In this model, slab rollback, or a related change in subduction geometry, promoted asthenospheric upwelling and mantle-wedge heating,

enhanced slab-derived fluid and melt fluxes, and contributed to distinctive subduction-related magmatism, granitoid generation, regional low-P/T metamorphism along the East Asian margin.

2. Magmatic constraints on slab rollback and testable predictions

Distinctive mid-Cretaceous magmatism in SW Japan provides the clearest magmatic evidence for a thermal and material anomaly related to subduction-zone processes. High-Mg andesites and adakitic rocks have been reported from the Kanmon and Sasayama groups have mineral K–Ar ages of ca. 100 Ma (Ohira, 1995), whereas andesites and dacites from the Kanmon Group yield K–Ar ages of ca. 105–107 Ma (Imaoka *et al.*, 1993). In the Kinki district, ca. 105 Ma Nb-rich lamprophyres, high-Nb basalts, and adakites have also been documented and interpreted in terms of subduction-related geodynamic processes (Imaoka *et al.*, 2014, 2017). These

Table 1 Reported K–Ar ages of mid-Cretaceous low-P/T metamorphic rocks from the Abukuma Mountains, with comparative data from the Takato–Shiojiri, Komagane, Mikawa, Iwakuni–Yanai, and Higo areas. Plutonic-rock ages are excluded. Where possible, ages were recalculated using the ^{40}K decay constants of Steiger and Jäger (1977). Abbreviations: Ms, muscovite; Bt, biotite; Hbl, hornblende (*sensu lato*).

ref	sample	rock type	mineral	K (wt%)	error (wt%)	⁴⁰ Ar rad. (10 ⁻⁶ cm ³ STP g ⁻¹)	Atm. ⁴⁰ Ar (%)	age (Ma)	error (Ma)	region/area
Itaya (2025)										
2002		pelitic schist	Ms	1.39	—	5.92 ± 0.18	48.7	106.6	3.8	Abukuma (Gosaisho)
2003		pelitic schist	Ms	0.96	—	3.76 ± 0.14	56.3	98.2	4.6	Abukuma (Gosaisho)
2005		psammitic schist	Ms	1.39	—	5.03 ± 0.14	45.3	90.9	3.0	Abukuma (Gosaisho)
2005		psammitic schist	Ms	1.39	—	5.07 ± 0.07	4.6	91.6	2.2	Abukuma (Gosaisho)
2102		meta Qz porphyry	Ms	5.11	—	18.98 ± 0.81	61.2	93.2	4.3	Abukuma (Gosaisho)
2103		meta Qz porphyry	Ms	6.81	—	23.98 ± 0.36	8.9	88.5	2.2	Abukuma (Gosaisho)
2106		limestone	Ms	2.13	—	7.63 ± 0.12	2.2	90.0	2.2	Abukuma (Gosaisho)
2107A		black schist	Ms	2.49	—	9.24 ± 0.21	36.0	93.2	2.8	Abukuma (Gosaisho)
2107B		black schist	Ms	3.47	—	13.18 ± 0.27	29.3	95.3	2.6	Abukuma (Gosaisho)
2108		siliceous schist	Ms	4.85	—	19.41 ± 0.39	29.4	100.3	2.8	Abukuma (Gosaisho)
2109		calcareous shale	Ms	2.75	—	11.67 ± 0.24	30.1	106.1	3.0	Abukuma (Gosaisho)
2109		calcareous shale	Ms	2.75	—	11.51 ± 0.25	33.4	104.8	3.0	Abukuma (Gosaisho)
2110		black shale	Ms	2.95	—	12.11 ± 0.17	2.7	102.8	2.4	Abukuma (Gosaisho)
2111		slate	Ms	2.78	—	11.12 ± 0.16	1.1	100.3	2.4	Abukuma (Gosaisho)
2111		slate	Ms	2.78	—	11.84 ± 0.25	31.3	106.6	3.0	Abukuma (Gosaisho)
2112		pelitic schist	Ms	2.83	—	10.24 ± 0.23	34.1	90.9	2.6	Abukuma (Gosaisho)
2112		pelitic schist	Bt	7.32	—	28.45 ± 0.40	3.0	97.5	2.3	Abukuma (Gosaisho)
2113		pelitic schist	Ms	1.97	—	5.94 ± 0.17	47.5	76.1	2.6	Abukuma (Gosaisho)
2114		pelitic schist	Ms	2.26	—	8.99 ± 0.50	68.8	99.7	5.7	Abukuma (Gosaisho)
2114		pelitic schist	Bt	7.54	—	30.03 ± 0.49	16.3	99.8	2.5	Abukuma (Gosaisho)
2115		Bt amphibolite	Bt	1.11	—	4.21 ± 0.13	49.9	95.1	3.5	Abukuma (Gosaisho)
2116		pelitic gneiss	Bt	7.35	—	28.12 ± 0.39	1.6	96.0	2.3	Abukuma (Takanuki)
Ueda <i>et al.</i> (1969)										
HT-(1)		Ms-Qz schist	Ms	4.67	—	12.91	—	119	—	Abukuma (Hitachi)
HT-(3)		Cal-Ms-Qz schist	Ms	3.86	—	8.76	—	107	—	Abukuma (Hitachi)
HT-(5)		Ms-Qz schist	Ms	4.78	—	16.10	—	107	—	Abukuma (Hitachi)
HT-(8)		Ms-Qz schist	Ms	5.95	—	6.06	—	110	—	Abukuma (Hitachi)
HT-(9)		Ms-Qz schist	Ms	3.72	—	7.02	—	120	—	Abukuma (Hitachi)
HT-(10)		Ms-Qz schist	Ms	6.17	—	5.34	—	106	—	Abukuma (Hitachi)
HT-(11)		Ms-Qz schist	Ms	5.01	—	9.96	—	105	—	Abukuma (Hitachi)
HT-442		Hbl gneiss	Bt	1.13	—	7.42	—	117	—	Abukuma (Hitachi)
HT-436		Bt schist	Bt	4.50	—	5.33	—	105	—	Abukuma (Hitachi)
HT-245		Ky-And-Sil-Bt gneiss	Bt	4.50	—	3.61	—	102	—	Abukuma (Hitachi)
HT-252		Bt-Hbl gneiss	Bt	6.75	—	5.36	—	110	—	Abukuma (Hitachi)
HT-84		Hbl-Bt gneiss	Bt	6.48	—	0.17	—	118	—	Abukuma (Hitachi)
Shibata and Uchiumi (1983)										
A1012		amphibolite	Hbl	0.147	—	0.678	71.8	115	5	Abukuma Mtns
A0802		Bt-Hbl gneiss	Hbl	0.623	—	2.59	28.4	103	4	Abukuma Mtns
A0802		Bt-Hbl gneiss	Bt	1.527	—	5.84	31.4	96	3.3	Abukuma Mtns
Banno and Miller (1965)										
AM 54081301		gneiss	Bt	5.63	—	—	—	RE-CALC	7.2	Takato–Shiojiri
HK 39082102		gneiss	Bt	7.68	—	—	—	93.2	7.2	Mikawa (Dando)
HK 38081212		gneiss	Bt	7.30	—	—	—	103.1	8.2	Mikawa (Dando)
HK 38083003		gneiss	Bt	6.42	—	—	—	93.1	7.2	Mikawa (Dando)
SB 61032405		gneiss	Bt	5.93	—	—	—	70.7	3.1	Mikawa (Dando)
SB 61032406		gneiss	Bt	7.00	—	—	—	64.7	3.1	Mikawa (Dando)
Shibata and Hayama (1968)										
54081411		Bt-Ms-Kfs schist	Bt	7.92	—	—	13.8	RE-CALC	—	Komagane
54072106		Bt-Ms-Kfs gneiss	Bt	7.85	—	—	13.1	60.5	—	Komagane
55072505		Bt-Ms-Crd-Kfs gneiss	Bt	7.34	—	—	39.9	65.6	—	Komagane (Hissori)
Owada <i>et al.</i> (2014)										
11071201		slate (Chl)	Ms	5.96	0.02	23.24 ± 0.38	12.5	99.4	2.6	Iwakuni–Yanai
9052502		pelitic schist (Chl-Bt)	Ms	2.41	0.02	8.63 ± 0.17	39	91.5	2.5	Iwakuni–Yanai
Shibata and Yamamoto (1965)										
Og 96D		Bt-Pl-Grt-Qz gneiss	Bt	5.06	—	—	8.2	108	9	Higo
			Bt	5.06	—	—	5.7	106	11	Higo
Nakajima <i>et al.</i> (1995)										
90030903		metapelite (Grt-Crd)	Bt	7.169	—	30.5	7.7	106.4	3.2	Higo
Nagakawa <i>et al.</i> (1997)										
502		Bt schist	Bt	5.813	0.116	24.74 ± 0.25	2.5	106.5	2.3	Higo
			Bt	6.344	0.127	27.24 ± 0.27	2.0	107.4	2.3	Higo
304		Bt schist	Bt	4.534	0.091	19.46 ± 0.20	3.1	107.4	2.3	Higo
503		Bt schist	Bt	1.763	0.035	6.886 ± 0.074	6.8	97.9	2.2	Higo
			Bt	1.790	0.036	7.238 ± 0.077	5.8	101.3	2.2	Higo
207		Bt schist	Bt	3.963	0.079	16.60 ± 0.16	3.4	104.8	2.3	Higo
			Bt	4.325	0.087	17.97 ± 0.18	3.9	104.0	2.3	Higo
TM1		Bt-Ms schist	Ms	6.437	0.129	27.44 ± 0.27	1.6	106.6	2.3	Higo
			Ms	7.869	0.157	34.57 ± 0.34	1.3	109.8	2.4	Higo
			Bt	7.030	0.141	29.44 ± 0.29	0.8	104.8	2.3	Higo
			Bt	7.100	0.142	30.53 ± 0.30	1.0	107.5	2.3	Higo
005		Bt-Hbl gneiss	Bt	4.441	0.089	18.58 ± 0.19	2.3	104.7	2.3	Higo
004		Crn rock	Bt	5.981	0.120	24.75 ± 0.25	2.1	103.6	2.3	Higo
			—	—	25.68 ± 0.26	2.1	107.4	2.3	Higo	
204		Grt amphibolite	Hbl	0.598	0.012	2.551 ± 0.027	6.0	106.7	2.3	Higo
			Bt	4.084	0.082	16.95 ± 0.17	3.7	104.0	2.3	Higo
01B		Bt gneiss	Bt	6.522	0.130	27.77 ± 0.28	1.4	106.5	2.3	Higo
302		Bt-Hbl gneiss	Bt	5.914	0.118	25.07 ± 0.25	1.8	106.1	2.3	Higo
402		Bt gneiss	Bt	6.105	0.122	25.71 ± 0.26	1.4	105.4	2.3	Higo
1801		Bt gneiss	Bt	6.564	0.131	27.51 ± 0.29	1.5	104.9	2.3	Higo
			Bt	6.298	0.126	26.09 ± 0.26	1.8	103.7	2.3	Higo
			Bt	5.341	0.107	21.98 ± 0.22	1.4	103.1	2.2	Higo
07D		Bt-Hbl gneiss	Bt	5.331	0.107	22.21 ± 0.22	1.7	104.3	2.3	Higo

rocks, distributed from Kanmon through Sasayama to Kyoto, occur in a belt broadly parallel to the northern margin of the low-P/T Ryoke metamorphic belt.

Slab rollback offers a plausible mechanism for this magmatic association. Kiminami and Imaoka (2013) documented Jurassic–Cretaceous magmatic variations along a ~1,000-km-long East Asian transect and suggested a transition from Jurassic shallow-angle to flat-slab subduction, followed by Early Cretaceous rollback. In this framework, asthenospheric upwelling and enhanced interactions among the mantle wedge, subducted oceanic crust, subducted sediments, and lower crust could have generated high-Nb basaltic magmas, adakitic melts, and high-Mg andesites (Imaoka *et al.*, 2014, 2017).

Similarly diverse Early Cretaceous magmatism in the Kitakami Mountains, including Sr-rich or adakitic andesites, high-Mg andesites, high-Nb andesites, and shoshonites, suggests that enhanced slab–mantle interactions were not restricted to SW Japan (Tsuchiya and Kanisawa, 1994; Mikoshiba, 2002; Tsuchiya *et al.*, 2005, 2007, 2015). Wang *et al.* (2023), however, interpreted the Early Cretaceous magmatic evolution of NE Japan in terms of transient slab break-off, mantle upwelling, and subsequent re-establishment of subduction rather than explicitly invoking slab rollback. This interpretation likewise invokes major reorganization of the subduction system and enhanced asthenospheric input, although its relationship to regional-scale rollback remains uncertain. Tsuchiya *et al.* (1997) identified two geochemically distinct types of olivine–augite basalt in the Lower Cretaceous Kanaegaura Formation on Oshima Island near Kesenuma. Basalt type 2 is more primitive and relatively enriched in incompatible elements relative to type 1, indicating a change in mantle source or melting conditions during the volcanic evolution of the formation. Although this change does not provide direct evidence for rollback, it is compatible with asthenospheric influx and reorganization of mantle-wedge flow. Alternative explanations, including small-scale mantle-source heterogeneity and changes in the degree or depth of partial melting, cannot be excluded.

Direct evidence for slab rollback has not been identified in the Abukuma belt. Nevertheless, its reconstructed position between the SW Japan and Kitakami segments of a broadly continuous Early Cretaceous convergent margin is significant in this context. If rollback operated at the scale of this margin, the Abukuma belt may have formed part of the same along-arc geodynamic system. A comparable Early Cretaceous thermal regime could also have influenced granitoid generation and low-P/T metamorphism. Suwa and Tsunogae (2026) showed that monazite ages from metamorphic rocks distributed across different

lithotectonic units and crustal levels of the Abukuma Mountains cluster at ca. 115–104 Ma, broadly overlapping with regional granitoid magmatism. They interpreted this temporal coherence as evidence for regionally extensive thermal reworking driven by a short-lived arc-related magmatic flare-up. Although their study did not identify the geodynamic mechanism responsible for the flare-up or explicitly invoke slab rollback, it provides direct evidence that regional low-P/T metamorphism was broadly coeval with magmatism across the Abukuma Mountains.

The petrogenetic characteristics of Cretaceous granitoids provide additional constraints on the sources of heat and material. Granitoids in the Iwakuni–Yanai and Gosaisho–Takanuki plutono-metamorphic belts belong largely to the ilmenite series, consistent with reduced crustal sources and metasedimentary anatexis (Ishihara, 1977; Nakajima *et al.*, 2016). This characteristic is not diagnostic of rollback. However, recent Pb–Sr–Nd–Hf isotope data and geochemical mass-balance modelling indicate that Cretaceous granitoids in SW Japan incorporated components derived from sediments and oceanic crust of the paleo-Pacific/Izanagi plate (Dao *et al.*, 2026). These observations are consistent with a combination of crustal melting and slab-derived material transfer, although they do not by themselves demonstrate that these processes were enhanced by rollback.

Regional contrasts provide testable predictions for the rollback model. The Gosaisho–Takanuki area of the southern Abukuma Mountains contains abundant Cretaceous plutonic rocks, including diorite, granodiorite, and gabbroic rocks (Takahashi *et al.*, 2016), whereas granitic rocks predominate in the Takato–Shiojiri, Iwakuni–Yanai, and Higo areas (e.g., Ono, 1977; Nakajima, 1994; Nagakawa *et al.*, 1997). The host-rock assemblages also differ among these regions, potentially influencing how magmatic heat and externally derived materials were transferred and recorded. If the rollback model is correct, coeval mafic to intermediate rocks, particularly in the Gosaisho–Takanuki and Higo areas, should preserve trace-element or isotopic evidence for enriched asthenospheric mantle input, slab-derived melts or fluids, or subducted-sediment components. The model further predicts systematic spatial or temporal migration of magmatism, evidence for regional extension, and temporal coupling among mantle-derived magmatism, granitoid generation, and low-P/T metamorphism. These predictions can be tested using structural analysis, trace-element geochemistry, Sr–Nd–Pb–Hf isotope systematics, zircon U–Pb geochronology, and zircon Hf isotope data.

3. Discussion

3.1. Evidence for a margin-scale thermal anomaly

The proposed >1,000-km-long tectono-thermal system is supported by the spatial and temporal association of low-P/T metamorphism and granitoid plutonism in the Gosaisho–Takanuki, Takato–Shiojiri, Iwakuni–Yanai, and Higo areas. In southern Abukuma Mountains, Miyashiro (1958) recognized progressive metamorphic zones in the Gosaisho–Takanuki area, ranging from greenschist-facies assemblages through amphibolite-facies assemblages to sillimanite + K-feldspar-bearing high-grade pelitic rocks. The new K–Ar ages suggest that the Gosaisho and Takanuki units of the Abukuma Metamorphic Rocks shared a common ca. 100 Ma thermal history after tectonic juxtaposition (Itaya, 2025). Similar low-P/T domains in the Takato–Shiojiri, Iwakuni–Yanai, and Higo areas are associated with Cretaceous plutonism and broadly overlap in age at ca. 110–95 Ma (e.g., Ono, 1977; Nakajima, 1994; Nagakawa *et al.*, 1997; Ikeda, 2004).

Metamorphic grade increases regionally from east to west in the Gosaisho–Takanuki area, from west to east in the Takato–Shiojiri area, and north to south in the Iwakuni–Yanai and Higo areas, rather than forming simple concentric aureoles around individual plutons (Miyashiro, 1958; Ono, 1977; Nakajima, 1994; Nagakawa *et al.*, 1997). Migmatites in the Iwakuni–Yanai and Higo areas, together with partial-melting textures in the Gosaisho–Takanuki area, further indicate substantial heat input near the highest-grade domains (Nakajima, 1994; Nagakawa *et al.*, 1997; Hiroi and Kishi, 1989). Recent reviews of the Ryoke metamorphic belt also indicate repeated magmatic pulses, variable emplacement depths, and changing crustal stress conditions rather than a single intrusive event (Okudaira *et al.*, 2024). Thermal modelling of the Iwakuni–Yanai area suggests that conductive heating from plutons was accompanied by thermal buffering during dehydration melting and advective heat transfer by upward melt migration (Ikeda *et al.*, 2026). These observations support a crustal-scale thermal anomaly rather than isolated contact metamorphism.

This interpretation is consistent with regional magmatic evidence. Distinctive ca. 105 Ma magmatism in SW Japan, together with Jurassic–Cretaceous magmatic patterns, is compatible with rollback-related asthenospheric upwelling and enhanced slab-derived fluxes (Kiminami and Imaoka, 2013; Imaoka *et al.*, 2014, 2017; Suga and Yeh, 2020). Detrital zircon U–Pb–Hf data from the South Kitakami Mountains of NE Japan also record a major Cretaceous arc event, including a 112 ± 22 Ma zircon age peak interpreted as reflecting magmatic flare-up, tectonic erosion, and crustal reworking (Pastor-

Galán *et al.*, 2021). Although not direct evidence for rollback, this record supports the existence of a broad Cretaceous arc-related crustal thermal event in NE Japan.

3.2. Phase-equilibrium constraints

The P–T pseudosections, calculated using representative average pelitic bulk compositions from the Gosaisho unit of the Abukuma Metamorphic Rocks and the Iwakuni–Yanai area of the Ryoke metamorphic belt, provide a thermodynamic comparison of two widely separated segments of the proposed plutono-metamorphic system (Fig. 2). Despite differences in bulk composition and modelling assumptions, both calculations predict the stability of diagnostic high-temperature, low-P/T assemblages, including sillimanite + K-feldspar and K-feldspar + cordierite. The predicted development of silicate melt at high temperatures is also consistent with field evidence for migmatization and partial melting in both regions.

Because the calculations use average bulk compositions, they are not intended to define precise P–T paths or establish a direct correlation between the two areas. Rather, they demonstrate that the characteristic high-grade assemblages and partial melting observed in both regions are thermodynamically compatible with broadly comparable low-P/T thermal conditions.

3.3. Global context of large-scale low-P/T plutono-metamorphic systems

Are large-scale low-P/T plutono-metamorphic systems restricted to the mid-Cretaceous East Asian continental margin? Comparable associations of low-P/T metamorphism, granitoid magmatism, mantle heat input, and crustal anatexis are recognized in accretionary and continental-margin orogens of different ages and regions.

The Tia Complex in eastern Australia provides a local example within the >1,000-km-long New England Orogen, where older accreted and metamorphic units were thermally overprinted under low-P/T conditions in association with granitoid magmatism (Watanabe and Hiram, 1988; Watanabe and Naka, 1988; Fukui *et al.*, 1993, 2012). This event has been interpreted as a consequence of eastward subduction-system migration and subsequent granitoid magmatism, broadly consistent with a rollback-related tectono-thermal setting (Fukui *et al.*, 2012).

The Central Asian Orogenic Belt provides another large-scale Phanerozoic comparison in which rollback-related or subduction-geometry-controlled magmatism has also been proposed. In Mongolia, the Khangay–Khentey Basin and Middle Gobi Volcano-plutonic Belt record Late Paleozoic–Early Mesozoic volcanic and plutonic magmatism related to subduction–accretion and

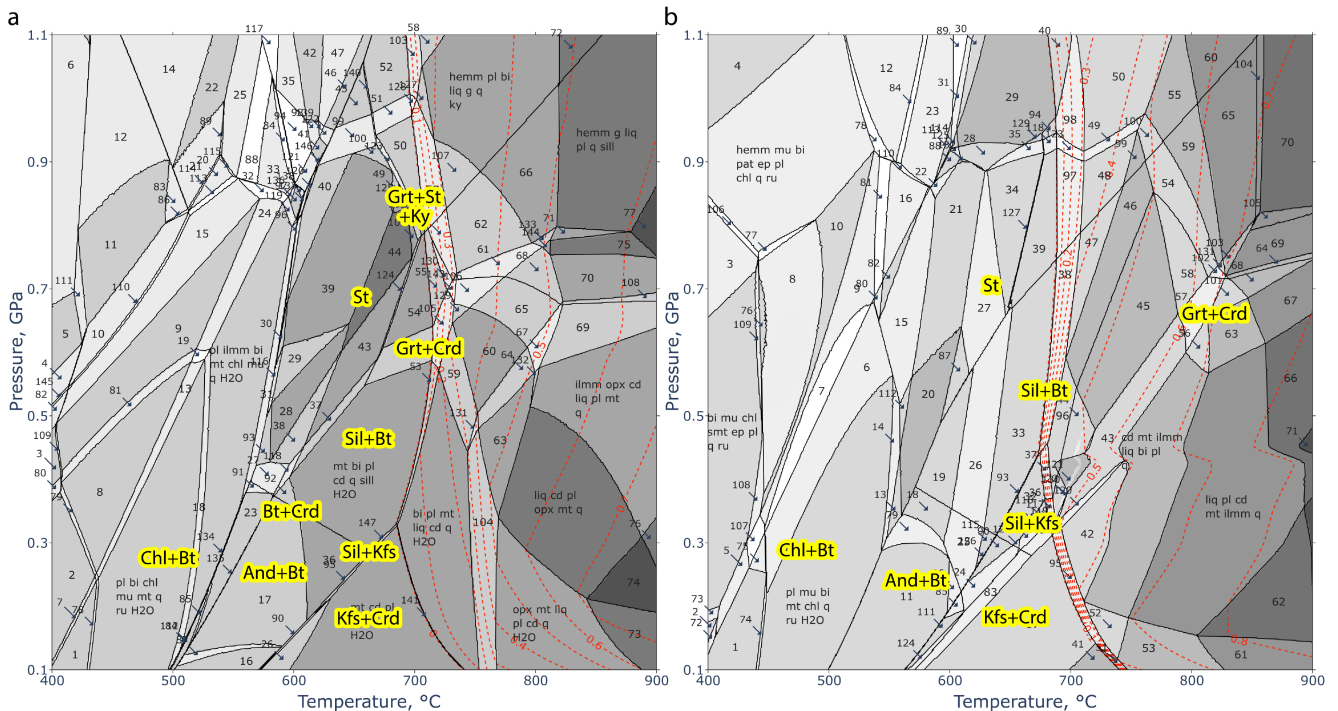


Fig. 2 Pressure–temperature (P–T) pseudosections in the Na_2O – CaO – K_2O – FeO – MgO – Al_2O_3 – SiO_2 – H_2O – TiO_2 – O_2 (NCKFMASHTO) system, calculated using average bulk compositions of pelitic metamorphic rocks, partly including psammitic compositions. Calculations were performed with MAGEMin (Riel *et al.*, 2022) using the ds62 metapelite thermodynamic dataset and solution models of White *et al.* (2014), with H_2O treated as an excess phase. (a) P–T pseudosection for the Abukuma Metamorphic Rocks (Gosaisho Unit), calculated using the average composition of ten pelitic samples from the Gosaisho Series of Miyashiro and Haramura (1962). The $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratio follows the average value reported by Miyashiro and Haramura (1962). (b) P–T pseudosection for the Iwakuni–Yanai area of the Ryoke metamorphic belt, calculated using the average composition of 20 samples from Kawakami and Ikeda (2003). For comparison with the Abukuma calculation, the $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratio of Miyashiro and Haramura (1962) was adopted, and MnO was excluded from the calculation. Approximate stability fields of key mineral assemblages, such as $\text{Sil} + \text{Kfs}$ and $\text{Kfs} + \text{Crd}$, are illustrated as levels. Tiny mineral abbreviations and numerical labels are the original MAGEMin outputs. Red dashed lines represent isopleths of the volume fraction of coexisting silicate melt. Because MnO was excluded, the stability fields of garnet-bearing assemblages, such as $\text{Grt} + \text{Crd}$, are shifted toward relatively higher temperature and pressure; nevertheless, the calculated metamorphic conditions for the Iwakuni–Yanai area are broadly consistent with the summary of Okudaira *et al.* (2024). Although the $\text{Ms} + \text{Crd}$ assemblage was not reproduced for the bulk composition used here, the calculated high-temperature limit of muscovite is also consistent with previous studies.

post-accretionary tectonics, including ilmenite-series granitoids and evidence for mantle heat input (Ganbat *et al.*, 2021, 2022). The Gobi Altai Mountains preserve regional low-P/T metamorphism in an accretionary complex (Nakano *et al.*, 2021), and episodic granitoid magmatism in the Ereendavaa Block has been linked to repeated tectono-magmatic events involving changes in subduction geometry and mantle heat influx (Bold *et al.*, 2025). Recent studies also show that flat-slab subduction and subsequent slab rollback can strongly influence overriding-plate deformation, extension, and surface evolution (Liu *et al.*, 2024; Zhang *et al.*, 2025). Although these examples do not directly document low-P/T plutono-metamorphic systems, they support the broader view that changes in subduction geometry can generate large-scale tectono-thermal and crustal responses.

Large-scale low-P/T plutono-metamorphic systems are not limited to Phanerozoic orogens. The Paleoproterozoic Wopmay Orogen of northwestern Canada, extending for ~500 km along strike, provides an

older example of coupling between crustal heating and plutonism. Low-P/T metamorphism is spatially associated with voluminous peraluminous plutonism and metasedimentary anatexis, and metamorphic grade increases toward the Hepburn batholith (Hoffman, 1989; St-Onge, 1984; St-Onge and Davis, 2017; Lalonde, 1989; Hildebrand *et al.*, 2010). Although smaller in scale and with a less tightly constrained temporal relationship than the Japanese case, the Wopmay Orogen indicates that such coupling has operated since at least the Paleoproterozoic.

These comparisons do not directly demonstrate a rollback-related origin for the Japanese system, but they strengthen its tectonic plausibility. They show that large-scale low-P/T plutono-metamorphic systems can develop repeatedly where changes in subduction geometry enhance mantle heat input, granitoid magmatism, crustal anatexis, and regional thermal overprinting. The Japanese >1,000-km-long mid-Cretaceous system may therefore represent one expression of a globally recurrent tectono-

thermal process.

3.4. Limitations and perspectives

The principal limitation of the proposed rollback-related interpretation is that diagnostic magmatic and isotopic evidence is unevenly distributed along the >1,000-km-long system. High-Nb basalts, adakites, high-Mg andesites, and isotopic evidence for subducted-sediment and oceanic-crust contributions to granitoid magmatism are best documented in SW Japan (Ohira, 1995; Imaoka *et al.*, 2014, 2017; Dao *et al.*, 2026). Comparable trace-element and isotopic datasets, however, remain limited for the Gosaisho–Takanuki and Higo areas. Moreover, although the temporal association between Cretaceous magmatism and regional low-P/T metamorphism in the Abukuma Mountains is increasingly well constrained, the plate-scale mechanism responsible for this thermal and magmatic pulse remains uncertain. Wang *et al.* (2023) interpreted the Early Cretaceous magmatic evolution of NE Japan in terms of transient slab break-off, mantle upwelling, and subsequent re-establishment of subduction, whereas Suwa and Tsunogae (2026) attributed regional metamorphic reworking at ca. 115–104 Ma to a short-lived arc-related magmatic flare-up without specifying its plate-tectonic cause. Together, these interpretations are consistent with enhanced magmatic heat input and substantial reorganization of the subduction system, but neither provides diagnostic evidence for rollback.

If the proposed rollback-related origin is correct, mafic to intermediate rocks in the Gosaisho–Takanuki and Higo areas should preserve geochemical evidence for enriched asthenospheric mantle input, slab-derived melts or fluids, or subducted-sediment contributions. In the southern Abukuma Mountains, zircon U–Pb ages of plutonic rocks provide an important chronological framework for Cretaceous magmatism (Takahashi *et al.*, 2016; Wang *et al.*, 2023), while monazite geochronology demonstrates that metamorphic rocks from different lithotectonic units and crustal levels record a broadly synchronous thermal event at ca. 115–104 Ma (Suwa and Tsunogae, 2026). However, direct evidence linking metamorphism, deformation, coeval plutonism, and magma sources to a specific plate-scale geodynamic mechanism remains limited. In the Higo area, the temporal relationships among low-P/T metamorphism, granitoid emplacement, and possible mafic magmatism also require further testing.

Further evaluation requires integrated petrological, structural, geochronological, and geochemical datasets from less well-studied segments of the proposed system. These datasets should include structural analyses, trace-element geochemistry, Sr–Nd–Pb–Hf isotope systematics,

zircon U–Pb geochronology, zircon Hf isotope data, and conventional K–Ar cooling ages of metamorphic and plutonic rocks. Particular attention should be given to possible spatial or temporal migration of magmatism and metamorphism, regional extensional structures, and the temporal relationships among mantle-derived magmatism, granitoid generation, deformation, and low-P/T metamorphism.

Conventional mica K–Ar dating remains useful for reconstructing regional cooling histories and spatial age-polarity patterns. It can also provide insight into Ar systematics during metamorphism, including Ar retention, loss, resetting, redistribution, and possible excess-Ar incorporation. The K–Ar dataset of Itaya (2025) from the Abukuma Metamorphic Rocks illustrates this complexity, indicating that mica ages may record not only post-metamorphic cooling but also variable Ar redistribution during the mid-Cretaceous thermal event. Such geochronological constraints, when integrated with petrological, structural, and geochemical datasets, are essential for assessing the scale, timing, and mechanism of the proposed tectono-thermal system.

4. Conclusions

The Gosaisho–Takanuki, Takato–Shiojiri, Iwakuni–Yanai, and Higo areas collectively define a >1,000-km-long, mid-Cretaceous low-P/T plutono-metamorphic system along the East Asian margin. Using the Gosaisho–Takanuki K–Ar framework as a chronological anchor, we propose that slab rollback, or a related change in subduction geometry, enhanced mantle-wedge heating and slab-derived fluid and melt fluxes, thereby contributing to granitoid magmatism and regional low-P/T metamorphism. The existence of this margin-scale plutono-metamorphic system is supported by the broadly coeval metamorphic and plutonic records of the four regions, although its rollback-related origin is currently best supported in SW Japan. The model's applicability to the Gosaisho–Takanuki and Higo areas remains to be tested through integrated petrological, geochronological, and geochemical studies of mafic to intermediate rocks and associated granitoids.

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東アジア縁辺部に沿う全長 1,000 km 超の中期白亜紀低 P/T 型深成—変成作用システム

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日本語要旨 阿武隈山地南部, 御斎所—竹貫地域の阿武隈変成岩類の K–Ar 年代は, 東アジア縁辺部における中期白亜紀の低 P/T 型変成作用と花崗岩質マグマティズムを再評価するための年代学的基準となりうる。御斎所—竹貫地域 (阿武隈変成帯), 高遠—塩尻地域 (領家変成帯), 岩国—柳井地域 (領家変成帯), 肥後地域 (肥後変成帯) では, 低 P/T 型変成作用と花崗岩質深成岩体形成が広く同時期に生じており, これらは大陸縁辺スケールの深成—変成作用システムを構成する。本稿では, スラブロールバック, あるいはそれに類する沈み込み形状の変化によって, アセノスフェアの上昇とマントルウェッジの加熱が促進されるなどして形成した長大な低 P/T 型深成—変成作用システムを提案する。この仮説は, 高 Nb 玄武岩質マグマ, アダカイト, 高 Mg 安山岩, および白亜紀花崗岩類におけるスラブ由来成分の同位体証拠が報告されている西南日本で最もよく支持される。この仮説をさらに検証するためには, 研究データに乏しい領域から, K–Ar 年代が示すような岩体の冷却年代も含めて総合的な岩石学的・年代学的・地球化学的データセットを得る必要がある。それらは構造発達と熱進化の規模と機構を評価するうえで不可欠である。

キーワード: 阿武隈変成岩類, 低 P/T 型変成作用, 中期白亜紀花崗岩マグマティズム, スラブロールバック, 沈み込みジオメトリ