Multi-OSL-thermochronometry using deep borehole core for thremal history over 0.1 Myr in Rokko Mountains

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Multi-OSL thermochronometry using deep borehole core

Optically stimulated luminescence (OSL) thermochronometry is a tool for constraining cooling histories in low-temperature domains (several tens of degree Celsius) during the past 10^4–10^5 years [1][2]. OSL thermochronometry is currently applied only to rapidly denuded regions (~5 mm/yr when a geothermal gradient is assumed to be ~30 °C/km), because the luminescence signals in slowly denuded regions saturate before the rocks are exhumated to the surface. However, estimating slow cooling histories may be possible if OSL signals of samples from deep boreholes at multiple depths are measured and evaluated with geothermal temperature in depth [3]. We applied multi-OSL-thermochronometry [4][5] to the deep borehole core drilled at the Rokko Mountains, Japan [6][7]. The denudation rates at this region is estimated to be ~0.5 mm/yr, which is slow for OSL-thermochronometry, from previous studies [7][8][9]. Multi-OSL thermochronometry applies the multi-elevated-temperature (MET) protocol [10]. The different MET signals measured for a single mineral of a sample have different closure temperatures, and thus provide multiple constrains on recent histories.

[1] Herman et al. (2010). Earth and Planetary Science Letters. [2] Herman and King (2018). Elements. [3] Guralnik et al. (2015). Earth and Planetary Science Letters. [4] Li and Li (2012). Tectonophysics. [5] King et al. (2016). Quaternary Geochronology. [6] Yamada et al. (2012) Technical note of the NIED. [7] Sueoka et al. (2010). Journal of Geography. [8] Matsushi et al. (2014). Transactions, Japanese Geomorphological Union. [9] Huzita and Kasama (1982). Geol. Surv. Japan. [10] Li and Li (2011). Quaternary Geochronology. [11] Ogata and Sueoka (2021). RADIOISOTOPES.

Equation for OSL thermochronometry of feldspar

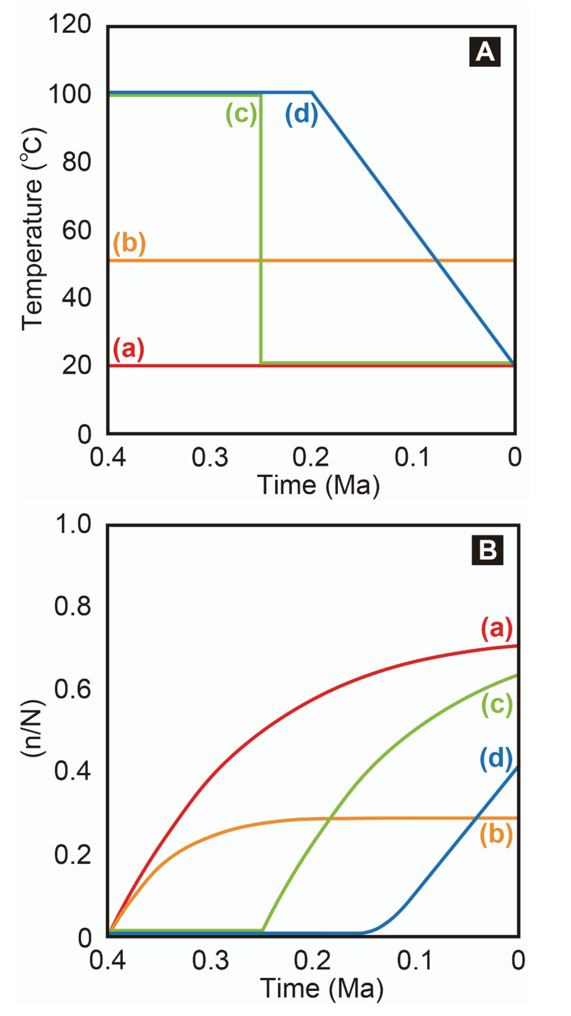
$$\frac{d\tilde{n}}{dt} = Trapping - Thermal\ detrapping - Athermal\ detrapping$$

First-order (exponential) kinetic model for Trapping

Band-tail states model for Thermal detrapping

$$\frac{d\tilde{n}}{dt} = \frac{\dot{D}}{D_0}\cdot(1-\tilde{n}) - s_{th}\cdot\tilde{n}\cdot exp\left(\frac{E_b-E_t}{kT}\right) - s_{tun}\cdot\tilde{n}\cdot exp\left(\rho'^{-\frac{1}{3}}\cdot r'\right)$$

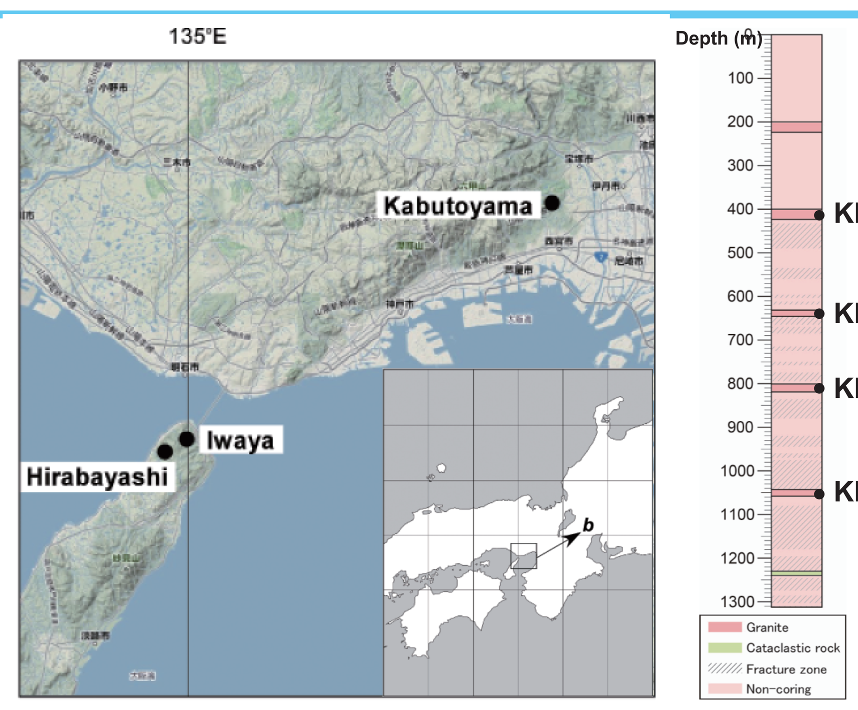
- $\tilde{n}$: The ratio of trapped electrons in the total trap
- $\dot{D}$: The dose rate of radiation (Gy/ka)
- D_0: The characteristic dose of saturation (Gy)
- s_{th}: The frequency factor for thermal decay
- s_{tun}: The frequency factor for athermal decay
- t: Time
- k : Boltzmann's constant
- E_b: Band-tail state energy level (eV)
- E_t: Trap depth (eV)
- T: Temperature (K)



Schematic diagrams of (A) thermal scenarios and (B) predicted (n/N) accumulations from the thermal scenarios [11].

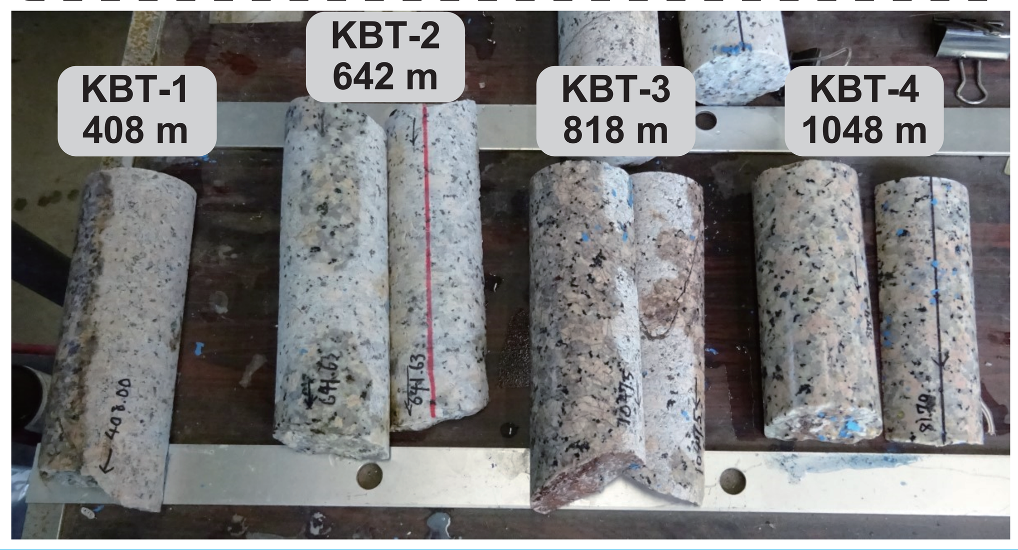
Rokko region

The denudation rate at the Rokko region is estimated to be 0.04-0.10 mm/y (10^7 years) [7] and 0.37-0.81 mm/yr (10^2–10^4 years) [8] by apatite fission track and terrestrial cosmogenic nuclide methods, respectively. Rokko Mountains have been uplifted by 500 m by faulting since 1 Ma (~0.5 mm/yr) [9]. The denudation rates at this region is estimated to be ~0.5 mm/yr from these previous studies. We used the Kabutoyama core collected by National Research Institute for Earth Science and Disaster Resilience [6]. We collected the samples at 408, 642, 818 and 1048 m with the ambient sampling temperature ($T_{in-situ}$), which is based on the temperature measurement of borehole, of 23, 28, 33 and 38 °C, respectively, for OSL-thermochronometry.



Location map of the sampling site [6] and columnar section and sampling points of the Kabutoyama core.

Driliing Point : Kabutoyama, Nishinomiya, Hyogo
Drilling Depth: 1313.2 m
Sampling Depth : 408, 642, 818, 1048 m



Thermal history analysis of multi-OSL-thermochronometry

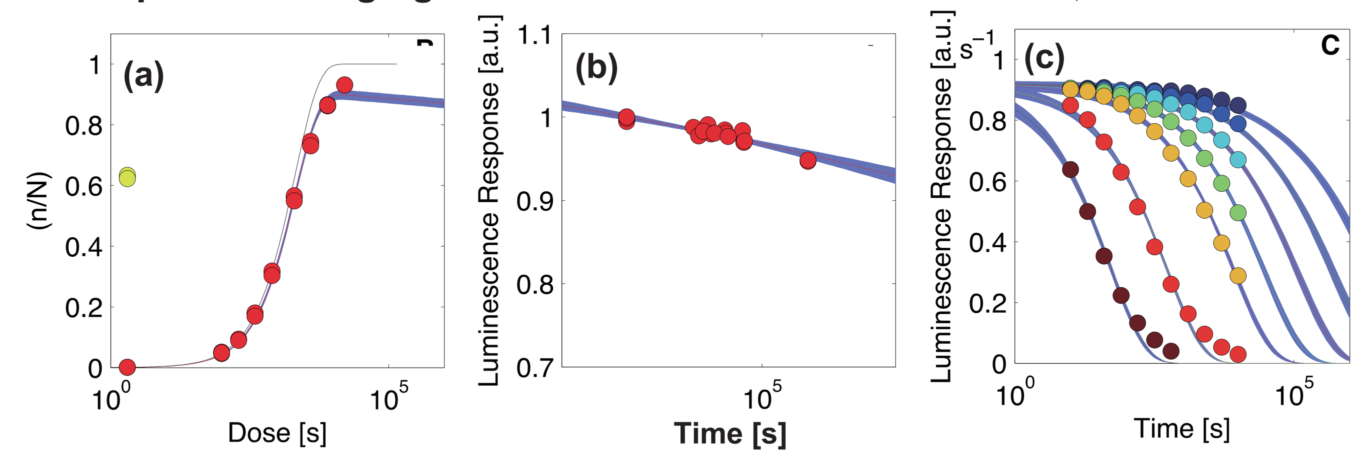
OSL experimental conditions

Instrument: Risø TL/OSL-DA-20
Light source: IR LEDs
Beta doses: $^{90}Sr/^{90}Y$ (0.1 Gy/s)
Measured mineral: Feldspar
Filter: Schott BG3 and BF39
Heat assist: 50, 100, 150, 225 °C
Preheat: 250 °C for 60s

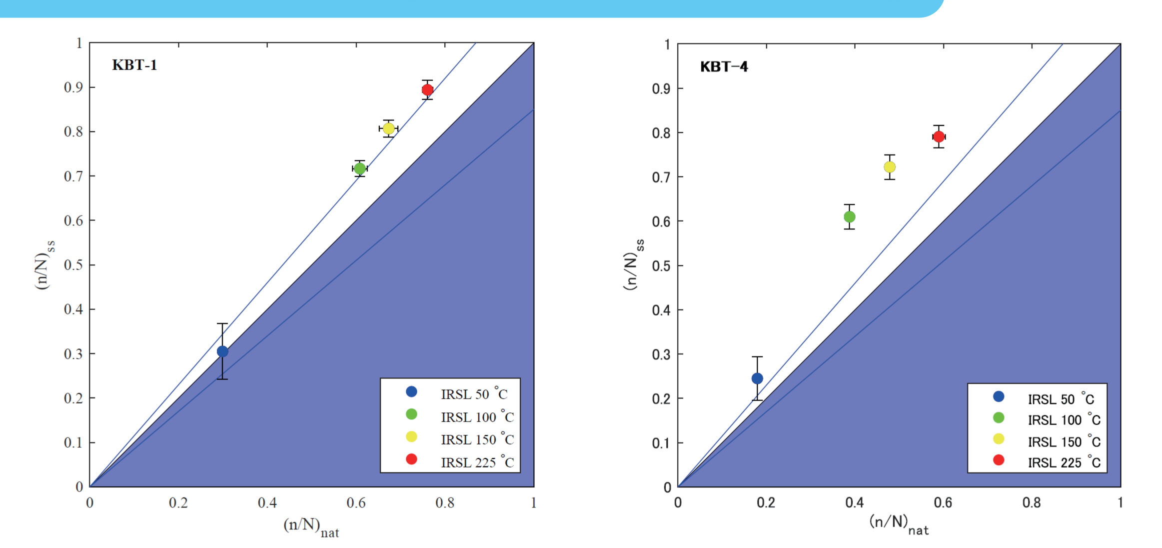
Laboratory Experiments

To determine the luminescence parameters of each sample for each IR signal, we carried out following experiments.

(a) Luminescence dose response measurements
 -Beta dose were given from 20 to 3600 Gy in a SAR protocol [12]
(b) Fading measurements
 -Regenerative dose was 200 Gy and test dose was 100Gy.
(b) Isothermal decay measurements
 -Temperature ranging from 170 to 350 °C for times of 0-10,240s.



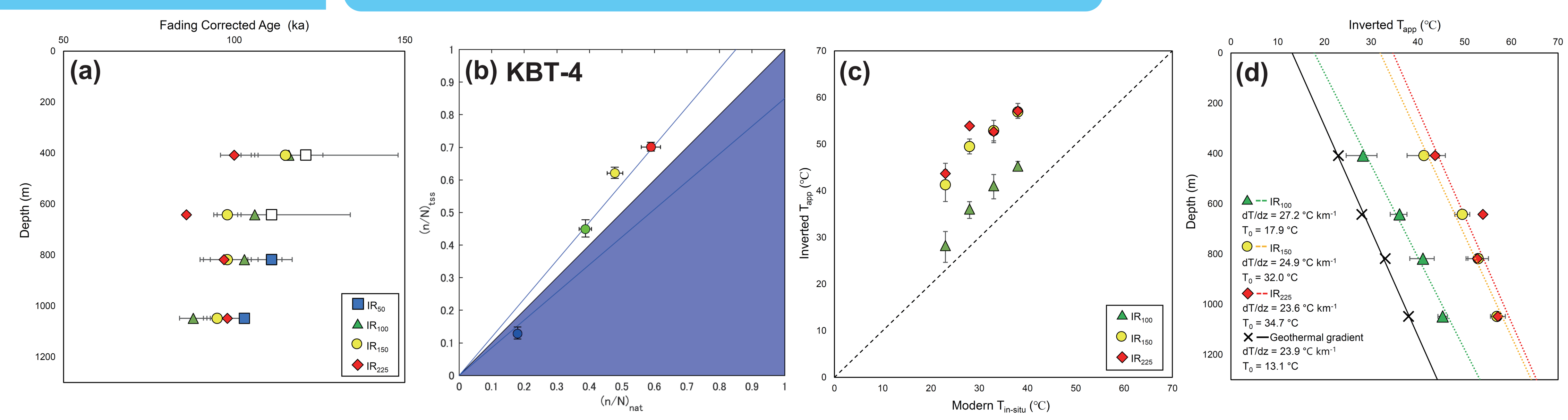
Athermal detrapping (Anomalous Fading)



Athermal signal depletion dose not relate to thermal signal. To screen signals of samples, athermal field saturation values, $(n/N)_{ss}$, were calculated with the fading model [13][14]. IR_{50} signals of KBT-1 and 2 are saturated in athermal steady state.

[12] Murray and Wintle (2000). Radiat. Meas. [13] Huntley (2006). J. Phy.: Condens. Matter. [14] Kars et al. (2008). Radiat. Meas.

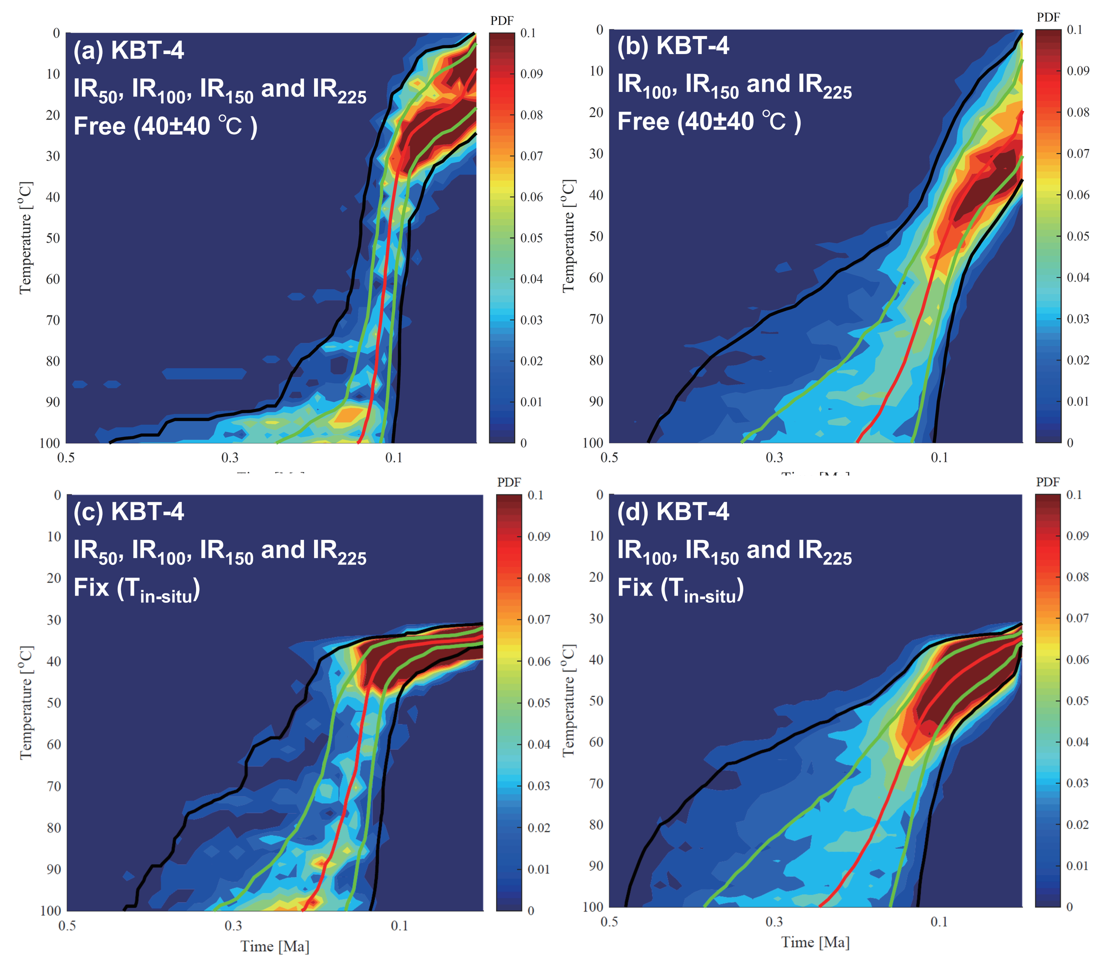
Estimation of apparent age and temperature



(a) Apparent age (fading corrected age) with depth. Open squares show the saturation in athermal steady state and minimum age calculated by 85% of $(n/N)_{ss}$. IR_{50} and IR_{100} signals decrease with depth, which might indicate the partial retention zone. (b) The plot of measured $(n/N)_{nat}$ vs. the ratio of trapped electrons in the total trap in thermal-steady state, $(n/N)_{tss}$, for KBT-4. $(n/N)_{tss}$ were calculated assuming that the temperature remained unchanged in the last 1.0 Myr. Most of IR signals of all samples are within 15% of 1:1 line, which indicate IR signals are in equibrium state in thermal steady state within the resolution of OSL thermochronometry. (c) The ambient sampling temperatures, $T_{in-situ}$, vs. inverted T_{app}. T_{app} were calculated assuming that the temperature remained unchanged in the last 1.0 Myr. IR_{50} signals are avoided because $(n/N)_{nat}$ are smaller than 85% of $(n/N)_{tss}$. Although T_{app} of all IR signals are bigger than those of $T_{in-situ}$, T_{app} increase with $T_{in-situ}$. (d) T_{app} with depth. Geothermal gradients estimated by T_{app} are consistent with geothermal gradient based on the ambient sampling temperature, however, the sureface temperatures are different. The results of (b)(c)(d) indicate that the growth of IR signals is in equilibrium state. The Rokko region is estimated to be thermal-steady state within the resolution of OSL thermochronometry, which is consistent with the estimated denudation rate (~0.5 mm/yr) at the Rokko region. The overestimation of the apparent temperature may be caused by the tendency to underestimate the effect of temperature on OSL signals with our physical model, or the uncertainties in the derivation of the thermal kinetic parameters.

Attempt to apply inversion modeling

We attempted to apply the Bayesian inversion approach to construct a probability density function for cooling histories [2][5]. This approach has been applied to rapidly denuded regions (> several mm/yr) successfully, however, not applied to slowly denuded regions. The inversion modeling were carried out while changing conditions of used signals and the set final temperature (T_f). The limit age is estimated to be ~0.1 Ma based on 85% of $(n/N)_{ss}$. When the final temperature is free (40±40 °C; (a)(b)), we could not recover $T_{in-situ}$. T_f using three signals are more close to $T_{in-situ}$ than T_f using all signals and this may be because of avoiding IR_{50} signals which is unstable. When the T_f is fixed ($T_{in-situ}$; (c)(d)), the results of all signals are consistent with the slow denudation rate at the Rokko region. While the results of three signals show rapidly denudation rate, which is not consistent with the Rokko region. This may be because of the underestimating of the effect of temperature to OSL signals for our physical model, or the uncertainties in the derivation of the thermal kinetic parameters.



Themal histories of KBT-4. The countor color show probability density. Red lines show the median mode, green show 60% quantile and black show 90% quantile.

Conclusions

- The results of estimation of apparent tempearture indicate that multi-OSL-thermochronometry can estimate the thermal history of the Rokko region. Precision of inverted parameters depend on characteristic of measured sample and/or used physical model and/or the uncertainties in the derivation of the thermal kinetic parameters. Selecting suitable IR signals by MET is needed to evaluate thermal history accurately. However, the denudation rate in the Rokko region was too low and could not be determined by OSL-thermochronometry. Other low-temperature thernochronometry methods with the older age limit than OSL is needed to determine denudation rate at the Rokko region (e.g., electron spin resonance [15]).
- Estimating the slow denuded region using the Bayesian inversion modeling requires selecting IR signals suitable for used physical model and accurate ambient sampling temperature.

[15] King et al. (2020). Geochronology.

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