On approximations of EASY%Ro solutions to estimate maximum temperature from vitrinite reflectance

Shunya Kaneki* and Hiroyuki Noda*

Received April 23, 2020
Accepted July 29, 2020
* Disaster Prevention Research Institute, Kyoto University, Uji 611-0011, Japan

Corresponding author: S. Kaneki, kaneki.shunya.62a@st.kyoto-u.ac.jp

Abstract: Vitrinite reflectance Ro is commonly used as a paleotemperature proxy for rocks. Among various models used to reconstruct paleothermal histories, EASY%Ro, a set of ordinary differential equations to describe the maturation of vitrinite, has been widely used since 1990. Approximations of EASY%Ro solutions employing specific paleothermal histories have been used in the field of structural geology to estimate maximum paleotemperatures \( T_{\text{max}} \). However, comparisons of those approximations with results obtained with EASY%Ro have not been reported in scientific literatures, and the errors on the approximations and the limitations of their use to determine \( T_{\text{max}} \) remain undocumented. Here, we performed such comparisons and found that the use of those approximations can lead to considerable deviations from the results obtained with EASY%Ro. We then derived new approximations of EASY%Ro solutions for four representative paleothermal histories that provided estimates of \( T_{\text{max}} \) within 3 °C of those obtained with EASY%Ro. We also describe the Jacobian of EASY%Ro, which can be used to propagate errors from \( R_o \) to \( T_{\text{max}} \). We expect that the four approximations provided herein will be useful, although we recommend using EASY%Ro itself if greater precision or particular paleothermal histories other than those assumed in this study are required.

Keywords: Vitrinite reflectance, Paleothermal history, EASY%Ro, Approximation

Introduction

Because organic matter is a common constituent of sediments, vitrinite reflectance \( R_o \) is often used as a paleothermal indicator (e.g., Burnham et al., 2019). Models of the maturation of vitrinite can be classified into two types: time-independent models can be used to determine only the maximum temperature \( T_{\text{max}} \), to which sediments have been exposed (e.g., Barker, 1983; Price, 1983), whereas time-dependent models can be used to determine sediments’ paleothermal histories (the \( T(t) \) function; e.g., Sweeney and Burnham, 1990; Nielsen et al., 2017). Among time-dependent models, EASY%Ro proposed by Sweeney and Burnham (1990), which is a simplified version of VITRIMAT (Burnham and Sweeney, 1989), has been frequently applied to sedimentary and metamorphic rocks at various locations (e.g., Laughland and Underwood, 1993; Ohmori et al., 1997; Sakaguchi, 1999; Kondo et al., 2005; Yamamoto et al., 2005, 2017; Mukoyoshi et al., 2006, 2007; Rowe et al., 2009, 2011; Kitamura et al., 2014; Zhang et al., 2016; Chen et al., 2017; Kaniya et al., 2017, 2020). Some studies, such as Laughland and Underwood (1993) and Ohmori et al. (1997), proposed approximations for EASY%Ro solutions employing typical \( T(t) \) functions, which they used to estimate \( T_{\text{max}} \). Although these approximations have been used in many structural geology analyses, the limitations and approximation errors of this approach have not been reported in the scientific literature.

Here, we investigate those approximations. We first review the theory that underpins EASY%Ro, then examine the approximations developed by Laughland and Underwood (1993) and Ohmori et al. (1997) and report on the errors and limitations of those approximations. We show that the approximations of EASY%Ro solutions used in some previous studies include significantly large approximation errors, and suggest improvements to the approximate solutions for EASY%Ro that can be used to better calculate \( T_{\text{max}} \) from \( R_o \). However, because our approximations are applicable for \( T(t) \) of specific shapes, we recommend calculating the original EASY%Ro solution if greater precision or particular paleothermal histories other than those assumed in this study are required. Finally, we discuss the propagation of errors from measured \( R_o \) to calculated \( T_{\text{max}} \) values.

EASY%Ro, a model of vitrinite maturation

A first-order chemical reaction following the Arrhenius law is expressed as

\[
\frac{d\xi}{dt} = A(1-\xi)\exp\left(-\frac{E^*}{RT}\right),
\]

where \( \xi \) is the reacted fraction, \( t \) is time, \( A \) is the pre-ex-
ponential factor, $E_i^\Lambda$ is the activation energy, $R$ is the gas constant, and $T$ is absolute temperature, which is a function of time $t$. Sweeney and Burnham (1990) assumed that the complex maturation reaction of vitrinite can be expressed by a set of parallel first-order chemical reactions, each with the same value of $A$ but different values of $E_i^\Lambda$. The total reacted fraction $F$ as defined by Sweeney and Burnham (1990) (corrected in 1991) is

$$F = \sum_i f_i \xi_i,$$  

(2)

where the subscript $i$ represents the reaction component, $f_i$ is the weighting coefficient of the $i$-th component, and $\xi_i$ is the reacted fraction, which evolves according to

$$\frac{d\xi_i}{dt} = A(1 - \xi_i) \exp\left(-\frac{E_i^\Lambda}{RT}\right),$$  

(3)

where $E_i^\Lambda$ is the activation energy of the $i$-th component.

If we assume that $\xi_i = 0$ at $t = 0$, then the solution for Eq. (3) is

$$\xi_i = 1 - \exp\left[-A\int_0^t \exp\left(-\frac{E_i^\Lambda}{RT}\right)dt\right].$$  

(4)

The values of $f_i$, $A$, and $E_i^\Lambda$ are given by Sweeney and Burnham (1990). Finally, the vitrinite reflectance $R_c$ can be calculated as

$$R_c (%) = \exp(-1.6 + 3.7F).$$  

(5)

$R_c$ can take values from 0.20% to 4.7%.

In general, $T$ can be a complex function of $t$, and the integral in Eq. (4) is difficult to calculate analytically. Sweeney and Burnham (1990) approximated $T(t)$ as the piecewise linear function

$$T(t) = a_j + b_j t (t_{j-1} \leq t \leq t_j),$$  

(6)

where $a_j$ and $b_j$ are constants, the subscript $j$ indicates time windows, and $t_0 = 0$ is the beginning of vitrinite maturation. In a time window where $b_j \neq 0$, Eqs. (4) and (6) yield

$$\xi_i = 1 - \prod_j \xi_i - \prod_j \exp\left[-A\int_{t_j}^{t_{j+1}} \exp\left(-\frac{E_i^\Lambda}{RT}\right)dt\right]$$

$$= 1 - \prod_j \left(1 - \exp\left(-A\frac{T_{j+1} - T_j}{b_j} \exp\left(-\frac{E_i^\Lambda}{RT_j}\right)\right)\right) \frac{T_{j-1} - T_j}{b_j} \exp\left(-\frac{E_i^\Lambda}{RT_{j-1}}\right) \exp\left(-\frac{E_i^\Lambda}{RT_j}\right) \exp\left(-\frac{E_i^\Lambda}{RT_{j+1}}\right),$$  

(7)

where $T_j = a_j + b_j t_j$ is temperature at $t = t_j$. $E_i(x)$ is the exponential integral expressed as

$$E_i(x) = \int_{-\infty}^{x} \exp\left(-\frac{t}{T}\right) dt.$$

(8)

Note that the argument of $E_i$ is always negative here. In a time window where $b_j = 0$ (i.e., $T$ remains constant $T = T_{j-1} = T_j$ in the range $t_{j-1} \leq t \leq t_j$), the time-increment factor $\xi_i$ becomes

$$\xi_i = \exp\left[-A(t_j - t_{j-1}) \exp\left(-\frac{E_i^\Lambda}{RT_j}\right)\right].$$  

(9)

Sweeney and Burnham (1990) used the approximation to $E_i(x)$ proposed by Hastings (1955),

$$-E_i(-x) \approx \frac{\exp(-x)}{x} \frac{A_0 + A_1 x + x^2}{B_0 + B_1 x + x^2} (1 \leq x < \infty),$$  

(10)

where $A_0 = 0.250621$, $A_1 = 2.334733$, $B_0 = 1.681534$, and $B_1 = 3.330657$, which has a negligibly small relative error of less than $5 \times 10^{-5}$ (Hastings, 1955). Here, we used the open-source Python function scipy.special.expi (SciPy v1.4.1) to calculate $E_i(x)$.

To estimate $T_{max}$ from $R_c$, we must assume the shape of the $T(t)$ function. For this purpose, we examine two simple functions (Fig. 1): (1) a boxcar paleothermal history (constant $T$), and (2) a triangular paleothermal history (constant $|T|$). For simplicity, we assume the initial and present temperatures to be identical at $T_0$. The duration $t_i$ is defined by $T > T_{max} = T_i$ where we choose the frequently adopted $T_0$ value of 14.4 °C following Sekiguchi and Hirai (1980), who reported that the progress of vitrinite maturation at $T < T_{max} = 14.4$ °C is negligible by assuming a different model from EASY%R, and a linear $T(t)$ function. We confirmed that reaction progress at $T < T_{max} = 14.4$ °C is also negligible for the case.
of EASY%Ro model. The important feature of Eq. (4) is that the reacted fraction \( \xi \) depends only on the selection of either function (1) or (2), \( T_0 \), \( T_{\max} \), and \( t_d \), so that the other properties of \( T(t) \), such as the timing of the high-\( T \) event in the case of constant \( T \) and the skewness of the triangle in the case of constant \( |T'| \), are not important. If, after selecting either function (1) or (2), \( T_0 \) is so small that the reaction rate is negligible at \( T = T_0 \), the present value of \( R_o \) is a function only of \( t_d \) and \( T_{\max} \). We then assume that for a vitrinite particle deposited on the seafloor, initial values of \( F \) and \( R_o \) are 0 and 0.20%. Because temperatures of seafloor sediments are ranged 0.9–5.7 °C (Dutkiewicz et al., 2015) and difference between the EASY%Ro solutions with \( T_0 = 0 \) °C and 6 °C is negligible, we adopted \( T_0 = 0 \) °C. We then calculate \( R_o \) for 15 °C ≤ \( T_{\max} \) ≤ 350 °C at intervals of less than 1 °C.

**Approximations of EASY%Ro solutions**

Ohmori et al. (1997) approximated the EASY%Ro solution as

\[
T_{\max} [^\circ C] = 172 \log_{10} (R_o [%]) + 129, \tag{11}
\]

for \( t_d = 40 \) Myr and constant \( T \). Comparison of Eq. (11) with the EASY%Ro solution (Fig. 2a and 2b) shows that for \( R_o \) ranges reported by them (0.6% ≤ \( R_o \) ≤ 3.0%), the absolute approximation error of \( T_{\max} \) was less than 5 °C (Fig. 2b).

Laughland and Underwood (1993) described \( T_{\max} \) as a
function of $R_o$ for durations of 1 and 10 Myr as

$$T_{\text{max}}[^\circ C] = 93 \ln(R_o [%]) + 174 \ (t_d = 1 \text{ Myr}), \ (12)$$

$$T_{\text{max}}[^\circ C] = 90 \ln(R_o [%]) + 158 \ (t_d = 10 \text{ Myr}). \ (13)$$

Because they did not report the shape of the $T(t)$ function they assumed, we compared Eqs. (12) and (13) with the EASY%$R_o$ solutions for both the constant $T$ and constant $|T|$ cases (Fig. 2c-2f). Both approximations were significantly different from the EASY%$R_o$ solutions. Absolute errors of 5–34 $^\circ C$ for $R_o < 4.5\%$ (Fig. 2d and 2f) clearly indicate that Eqs. (12) and (13) are significantly different from EASY%$R_o$ solutions, and it is thus problematic to use these equations as approximations of EASY%$R_o$. The derivations of these equations were not described by Laughland and Underwood (1993), so we could not investigate the source of the deviation.

Here we develop approximations with smaller errors and wider applicable range of $R_o$. $T_{\text{max}}$ for constant $T$ and constant $|T|$ with $t_d = 1$ and 10 Myr can be approximated as

$$T_{\text{max}}[^\circ C] = \begin{cases} a_1 \ln(R_o [%]) + a_2 (0.30\% \leq R_o < 0.95\%) \\ b_1 \ln(R_o [%]) + b_2 (0.95\% \leq R_o < 2.23\%) \\ c_1 \ln(R_o [\%]) + c_2 (2.23\% \leq R_o \leq 4.60\%) \end{cases} \ , \ (14)$$

where $a_1$, $a_2$, $b_1$, $b_2$, $c_1$, $c_2$, and $c_3$ are coefficients that depend on the shape of the $T(t)$ function (Table 1) as determined by the least-squares fit obtained with scipy.optimize.curve_fit using the Levenberg-Marquardt algorithm (SciPy v1.4.1). The applicable ranges of $R_o$ were determined by trial and error, and continuity conditions at the boundaries were not postulated. Our comparisons of $T_{\text{max}}$ as a function of $R_o$ for the EASY%$R_o$ solutions and the approximations from Eq. (14) for the four cases (Fig. 3a and 3d) show that the absolute errors on the approximations were < 3 $^\circ C$ in all cases and <1 $^\circ C$ when $R_o \geq 1.0\%$ (Fig. 3b, 3c, 3e, and 3f).

### Table 1. Coefficients $a_1$, $a_2$, $b_1$, $b_2$, $c_1$, and $c_3$ determined by least-squares fitting of the three $T_{\text{max}}$ functions in Eq. (14).

| $t_d$ (Myr), functional | $a_1$ | $a_2$ | $b_1$ | $b_2$ | $c_1$ | $c_2$ | $c_3$ |
|-------------------------|-------|-------|-------|-------|-------|-------|-------|
| 1, constant $T$         | 89.6217 | 157.8367 | 73.5687 | 155.3964 | 43.2171 | 5.1890 | 228.4330 |
| 10, constant $T$        | 86.4091 | 142.3313 | 70.9247 | 139.9326 | 41.6867 | 5.1936 | 210.4055 |
| 1, constant $|T|$        | 89.4580 | 163.0534 | 73.2000 | 160.5780 | 42.9507 | 5.1925 | 233.2776 |
| 10, constant $|T|$       | 86.3489 | 147.6474 | 70.6520 | 145.2177 | 41.4947 | 5.1973 | 215.4540 |

### Error propagation from $R_o$ to $T_{\text{max}}$

Here we examine the errors on $T_{\text{max}}$ predicted by EASY%$R_o$ on the basis of measured $R_o$. Linearization of $T_{\text{max}}$ as a function of $R_o$ leads to

$$\delta T_{\text{max}} = \frac{dT_{\text{max}}}{dR_o} \delta R_o \ , \ (15)$$

where $\delta$ represents small differences. Oscillations in the numerically calculated Jacobian (Fig. 4) reflect the discreteness of $E_i^A$ values in EASY%$R_o$ (one peak in a wavy line corresponds to one reaction component). It would disappear if distribution of $E_i^A$ was continuous. The Jacobian is very large at low $R_o$ values, where maturation reactions have just started, and at high $R_o$ values, where they are almost complete. The Jacobian can be used to estimate the deviation, variance, and standard error of $T_{\text{max}}$ derived from measured $R_o$ if the linearization can be justified. For example, if the mean and standard error on $R_o$ are 2.0% and 0.3%, respectively, then the standard error on $T_{\text{max}}$ can be estimated as

$$\text{SE}(T_{\text{max}}) = \left| \frac{dT_{\text{max}}}{dR_o} \right| \ SE(R_o) \ , \ (16)$$

where $\text{SE}(x)$ is the standard error of $x$. In this case, this magnitude of measurement errors is significantly larger than the errors on approximations using Eq. (14).
Discussion and summary

The approximation proposed by Ohmori et al. (1997) (Eq. 11) agrees with the EASY%R_o solution with an absolute error of less than 5 °C for R_o which ranges reported by them (0.6% ≤ R_o ≤ 3.0%) (Fig. 2a and 2b). Outside this range of R_o, the absolute error increases dramatically and Eq. (11) is not applicable. The approximation errors of T_{max} in some previous studies, such as Kondo et al. (2005) and Rowe et al. (2011), cannot be even evaluated as they applied Eq. (11) to R_o values of 5.63% and 4.9%, respectively, which exceed the maximum allowed R_o value (4.7%) of EASY%R_o model. The approximations proposed by Laughland and Underwood (1993) (Eqs. 12 and 13) yield significantly higher T_{max} values than the EASY%R_o solutions (Fig. 2c–2f), with absolute errors of 5–34 °C for R_o < 4.5%. Eqs. (12) and (13) have been widely used in other studies (e.g., Sakaguchi, 1999; Yamamoto et al., 2005, 2017; Mukoyoshi et al., 2006, 2007; Rowe et al., 2009; Kitamura et al., 2014; Zhang et al., 2016; Chen et al., 2017; Kamiya et al., 2017, 2020). We suggest that implications made on the basis of erroneous T_{max} values in those studies require re-examination.

Laughland and Underwood (1993) compared the results of their two EASY%R_o approximations (Eqs. 12 and 13) with various vitrinite maturation models that were available in the early 1990s, including earlier simple models (e.g., Barker, 1983; Price, 1983), and reported the estimation error for T_{max} among these models to be 30 °C. More models have been proposed since then, and examination of them using better-calibrated data would be beneficial.
sets have shown EASY%Ro to work well (Burnham, 2019), although other improvements to EASY%Ro have recently been suggested (e.g., Nielsen et al., 2017). Some studies have adopted the $30\degree C$ as estimation error for $T_{\text{max}}$ determined by the approximations of either Eq. (12) or (13) (e.g., Mukoyoshi et al., 2007; Chen et al., 2017). As previously discussed, those approximations are significantly different from EASY%Ro solutions with large approximation errors. It is important to first estimate the $T_{\text{max}}$ error of a preferred model from the scatter of measured $R_o$ values by using the Jacobian of EASY%Ro results (e.g., Fig. 4). This estimation error should then be compared with model-dependent errors, which generally include not only the precision of EASY%Ro, but also the effects of the selected $T(t)$ functional form.

Although the approximations presented here (Eq. 14 and Table 1) are more accurate and cater to a wider range of $R_o$ than those of the previous studies discussed here, we constructed them for only four specific paleothermal histories. It should be noted that if the particular paleothermal history other than assumed in this study is plausible, such as nonlinear $T(t)$ or heating with much shorter timescale, our approximations should not be used to calculate $T_{\text{max}}$. Nonetheless, if our approximations are applicable, they provide $T_{\text{max}}$ solutions close to those obtained with EASY%Ro, differing from them by $3\degree C$ at most (Fig. 3). Furthermore, thanks to freely available resources such as Python, it is relatively simple to calculate $T_{\text{max}}$ using Eqs. (2), (4), and (5). If precision greater than that provided by our new approximations is required, or if a different paleothermal history from those assumed in this study is needed, we recommend using original EASY%Ro to calculate $T_{\text{max}}$. In this case, Fig. 4 may provide useful values of the estimation errors. Finally, we would like to note that although this study only focuses on EASY%Ro, there are other models useful to calculate $T_{\text{max}}$ from $R_o$ as examined by Burnham (2019).

Acknowledgement

We are grateful to Kosuke Egawa for handling this paper and two anonymous reviewers for giving useful comments. We thank Arito Sakaguchi for fruitful discussion about the preliminary results of our calculations. The Python code used for calculating EASY%Ro solutions in this study is available on a reasonable request to S.K. The contribution of S.K. to this project was supported by a Grant-in-Aid (KAKENHI No. 20J01284) for Fellows of the Japan Society for Promotion of Science.

References

Barker, C. E., 1983, Influence of time on metamorphism of sedimentary organic matter in liquid-dominated geothermal systems, western North America. Geology, 11, 384–388.
Burnham, A. K., 2019, Kinetic models of vitrinite, kerogen, and bitumen reflectance. Org. Geochem., 131, 50–59.
Burnham, A. K. and Sweeney, J. J., 1989, A chemical kinetic model of vitrinite maturation and reflectance. Geochim. Cosmochim. Acta, 53, 2649–2657.
Chen, W.-H., Huang, C.-Y., Yan, Y., Dilek, Y., Chen, D., Wang, M.-H., ..., Yu, M., 2017, Stratigraphy and provenance of forearc sequences in the Lichi Mélange, Coastal Range: Geological records of the active Taiwan arc-continent collision. J. Geophys. Res.: Solid Earth, 122, 7408–7436.
Dutkiewicz, A., Müller, R. D., O’Callaghan, S. and Jónasson, H., 2015, Census of seafloor sediments in the world’s ocean. Geology, 43, 795–798.
Hastings, C., 1955, Approximations for Digital Computers. Princeton University, Princeton, 201p.
Kamiya, N., Yamamoto, Y., Zhang, F. and Lin, W., 2020, Vitrinite reflectance and consolidation characteristics of the post-middle Miocene Forearc Basin in central and eastern Boso Peninsula, central Japan: Implications for basin subsidence. Isl. Arc, e12344. doi: 10.1111/ear.12344.
Kamiya, N., Yamamoto, Y., Wang, Q., Kurimoto, Y., Zhang, F. and Takemura, T., 2017, Major variations in vitrinite reflectance and consolidation characteristics within a post-middle Miocene forearc basin, central Japan: A geodynamical implication for basin evolution. Tectonophysics, 710–711, 69–
Approximations of EASY%Ro solutions. 661

Kitamura, M., Mukoyoshi, H. and Hirose, T., 2014, The relationship between displacement and thickness of faults in the Shimanto accretionary complex. J. Geol. Soc. Japan, 120, 11–21.*

Kondo, H., Kimura, G., Masago, H., Ohmori-Ikehara, K., Kitamura, Y., Ikawa, E., Okamoto, S., 2005, Deformation and fluid flow of a major out-of-sequence thrust located at seismogenic depth in an accretionary complex: Nobeoka Thrust in the Shimanto Belt, Kyushu, Japan. Tectonics, 24, TC6008, doi: 10.1029/2004TC001655.

Laughland, M. M. and Underwood, M. B., 1993, Vitrinite reflectance and estimates of paleotemperature within the Upper Shimanto Group, Muroto Peninsula, Shikoku, Japan. Geol. Soc. Am. Spec. Pap., 273, 25–44.

Mukoyoshi, H., Hara, H. and Ohmori-Ikehara, K., 2007, Quantitative estimation of temperature conditions for illite crystallinity: comparison to vitrinite reflectance from the Chichibu and Shimanto accretionary complexes, eastern Kyushu, Southwest Japan. Bull. Geol. Surv. Japan, 58, 23–31.*

Mukoyoshi, H., Sakaguchi, A., Otsuki, K., Hirono, T. and Soh, W., 2006, Co-seismic frictional melting along an out-of-sequence thrust in the Shimanto accretionary complex. Implications on the tsunamigenic potential of splay faults in modern subduction zones. Earth Planet. Sci. Lett., 245, 330–343.

Nielsen, S. B., Clausen, O. R. and McGregor, E., 2017, basin%Ro: A vitrinite reflectance model derived from basin and laboratory data. Basin Res., 29, 515–536.

Ohmori, K., Taira, A., Tokuyama, H., Sakaguchi, A., Okamura, M. and Aihara, A., 1997, Paleothermal structure of the Shimanto accretionary prism, Shikoku, Japan: Role of an out-of-sequence thrust. Geology, 25, 327–330.

Price, L. C., 1983, Geologic time as a parameter in organic metamorphism and vitrinite reflectance as an absolute paleogeothermometer. J. Pet. Geol., 6, 5–38.

Rowe, C. D., Meneghini, F. and Moore, J. C., 2009, Fluid-rich damage zone of an ancient out-of-sequence thrust, Kodiak Islands, Alaska. Tectonics, 28, TC1006, doi: 10.1029/2007TC002126.

Rowe, C. D., Meneghini, F. and Moore, J. C., 2011, Textural record of the seismic cycle: strain-rate variation in an ancient subduction thrust. Geol. Soc. London, Spec. Publ., 359, 77–95.

Sakaguchi, A., 1999, Thermal maturity in the Shimanto accretionary prism, southwest Japan, with the thermal change of the subducting slab: fluid inclusion and vitrinite reflectance study. Earth Planet. Sci. Lett., 173, 61–74.

Sekiguchi, K. and Hirai, A., 1980, Estimation of maturation level of organic matter. J. Japan. Assoc. Pet. Technol., 45, 39–47.*

Sweeney, J. J. and Burnham, A. K., 1990, Evaluation of a simple model of vitrinite reflectance based on chemical kinetics. Am. Assoc. Pet. Geol. Bull., 74, 1559–1570 (corrected in 1991, Am. Assoc. Pet. Geol. Bull., 75, 848).

Yamamoto, Y., Mukoyoshi, H. and Ogawa, Y., 2005, Structural characteristics of shallowly buried accretionary prism: Rapidly uplifted Neogene accreted sediments on the Miura-Boso Peninsula, central Japan. Tectonics, 24, TC5008, doi: 10.1029/2005TC001823.

Yamamoto, Y., Hamada, Y., Kamiya, N., Ojima, T., Chiyonobu, S. and Saito, S., 2017, Geothermal structure of the Miura-Boso plate subduction margin, central Japan. Tectonophysics, 710–711, 81–87.

Zhang, X., Cawood, P. A., Huang, C.-Y., Wang, Y., Yan, Y., Santosh, M.,...Yu, M., 2016, From convergent plate margin to arc–continent collision: Formation of the Kenting Melange, Southern Taiwan. Gondwana Res., 38, 171–182.

* in Japanese with English abstract.

Contributions

S.K. was the instigator of this investigation of the validity of the use of approximations of EASY%Ro solutions to determine Tma. The calculations reported here were cooperatively developed, validated, and performed by both authors. Both authors contributed to writing the manuscript.