Thermal considerations in inferring frictional heating from vitrinite reflectance and implications for shallow coseismic slip within the Nankai Subduction Zone

Patrick M. Fulton, Robert N. Harris

Abstract

Frictional properties within the upper few kilometers of subduction zones are generally thought to inhibit rupture propagation. Understanding whether large rapid slip propagates to the surface during megathrust earthquakes is important for characterizing tsunami hazard. Recent vitrinite reflectance analysis by Sakaguchi et al. (2011) on cores from the NanTroSEIZE drilling transect at the Nankai Trough, Japan, has been interpreted to suggest that these faults reached temperatures ~380 °C, considerably larger than background temperature values, implying they hosted coseismic slip at shallow depths. Analysis of other temperature proxies on the megasplay by Hirono et al. (2009), however, suggests temperatures have not exceeded 300 °C and is inconclusive as to whether the fault slipped at high velocity. We evaluate the effects of frictional heat generation on the spatial distribution of vitrinite reflectance, its sensitivity to slip zone thickness and slip duration, and the cumulative effects of numerous events. We build on the analysis of Sakaguchi et al. (2011) by estimating frictional heating scenarios that are consistent with both the peak and spatial extent of anomalous vitrinite reflectance data. Our results imply coseismic slip magnitudes of several 10s of meters. Peak temperature estimates from the vitrinite reflectance data can be reconciled with the other geochemical constraints only by assuming the vitrinite reflectance results from the cumulative effects of multiple earthquakes. However, this results in unrealistically large estimates of total displacement. Our results imply that current understanding of how vitrinite reflectance is affected by fault slip is incomplete.

1. Introduction

Understanding whether rapid fault slip propagates to shallow depths during large megathrust earthquakes is important for characterizing earthquake and tsunami hazard. Studies of fault mechanics at subduction zones generally suggest that the weak and velocity strengthening frictional properties within the shallow subduction zone inhibit rupture from propagating to the surface (Hyndman et al., 1997; Wang and He, 1999; Saffer and Marone, 2003). The 2011 Mw 9.0 Tohoku earthquake of northern Japan that exhibited very large slip all the way to the trench (Ito et al., 2011; Fujiwara et al., 2011) has challenged this view. A fundamental question resulting from this earthquake is whether the large amount of surface slip (~50 m) is rare and unique to this location or whether it characterizes the seismic potential of other subduction zones as well.

Because of limitations with the historical record of earthquakes and their dynamics, researchers have turned to paleoseismic techniques to characterize the geologic signature of seismic slip within fault zones. One set of paleoseismic techniques that appears particularly promising relies on proxy data that indicate temperature rise due to frictional heating. These proxies include vitrinite reflectance, fluid-mobile trace element concentrations, Sr isotopes, magnetic susceptibility, inorganic carbon content, Raman spectra of carbonaceous material, clay mineralogy, apatite fission tracks, extractable organic material, and pseudotachylite (e.g., d’Alessio et al., 2003; Di Toro et al., 2005; Mishima et al., 2006; Ishikawa et al., 2008; Hirono et al., 2009; Kuo et al., 2011; Sakaguchi et al., 2011; Polissar et al., 2011). Many of these methods often only constrain an upper or lower limit or a broad estimate range of peak temperatures resulting from frictional heating. Temperature rise is a useful indicator of rapid fault slip because the vast majority of energy dissipated due to frictional resistance during slip is converted to heat (e.g., Lachenbruch and Sass, 1980; Fulton and Rathbun, 2011). When these geothermometry techniques
are combined with thermal models of frictional heat generation, they hold the promise of placing constraints on fault slip parameters including slip magnitude, slip duration and the average shear stress during slip. Here, we focus on one of the most sensitive geothermometers, vitrinite reflectance, and on the Nankai Subduction Zone in southern Japan, where recent vitrinite reflectance analysis has been performed on Integrated Ocean Drilling Program (IODP) cores from the megasplay and frontal thrust (Sakaguchi et al., 2011) (Fig. 1). These data have been interpreted to suggest that the faults reached temperatures of 390 and 330°C, respectively, considerably larger than background values of 13 and 20°C (Kinoshita et al., 2009; Harris et al., 2011), implying that these faults hosted rapid slip at shallow depths. In contrast with this interpretation, analysis of other temperature proxies from the megasplay by Hirono et al. (2009) suggests temperatures have not exceeded 300°C and are inconclusive as to whether the fault slipped at high velocity. These other proxies, including fluid-mobile trace element concentrations, Sr isotopes, magnetic minerals, inorganic carbon content, and Raman spectra of carbonaceous material, do not reveal anomalous values within the inferred slip zone, but are insensitive to peak temperatures less than 300°C.

In this study, we show how patterns of vitrinite reflectance and other proxies for frictional heating may be used to better understand earthquake mechanics and yield quantitative information relevant to seismic and tsunami hazards. We start by describing patterns of frictional heating, illustrate how they are expected to be mapped into vitrinite reflectance, and conclude by evaluating the vitrinite reflectance data at Nankai in terms of characteristic slip parameters of each fault during large megathrust earthquakes. We first focus on estimating the frictional heat generation rate for reasonable combinations of slip duration and slip zone thickness and estimate a range of possible scenarios based on the peak and spatial extent of the anomalous vitrinite reflectance observations (Section 3). We then constrain the possible scenarios based on comparing the peak temperatures from the simulations with the upper bound based on the other geothermometry data. With the range of likely frictional heat generation scenarios constrained, we interpret the results in terms of slip and place additional constraints based on the estimates of total offset supported by each slip zone over geologic time. The resulting slip estimates are quite large and we conclude that this implies that either both faults host large rapid slip at shallow depths and/or that our current understanding of how fault slip affects vitrinite reflectance, as is commonly applied, needs to be better understood.

2. Methods

2.1. Temperature

When faults slip, the dissipated energy due to frictional resistance is converted to heat (e.g., Lachenbruch and Sass, 1980; Fulton and Rathbun, 2011) and can be characterized by the volumetric frictional heat generation rate within the slip zone, \( A_v (W/m^2) \), defined as,

\[
A_v = \frac{\tau v}{2a} = \frac{\tau u}{2\pi},
\]

where \( \tau \) is shear stress, \( a \) is the half-width of the slip zone, and \( v \) is the average slip velocity defined by the slip magnitude \( u \) across the whole slip zone divided by the slip duration \( t^* \). Anomalous temperature, \( T \), at distances \( x \) away from the center of the slip zone as a function of time, \( t \), can be expressed by (adapted from Carslaw and Jaeger, 1959 and Lachenbruch, 1980),

\[
T(x, t) = \frac{A_v}{\rho c} \left[ t \left[ 1 - 2^2 \text{erfc} \left( \frac{x+a}{\sqrt{4 \alpha t}} \right) - 2t^* \text{erfc} \left( \frac{x+a}{\sqrt{4 \alpha t^*}} \right) \right] - H(t-t^*) (t-t^*) \left[ 1 - 2t^* \text{erfc} \left( \frac{x-a}{\sqrt{4 \alpha t^*}} \right) - 2t^* \text{erfc} \left( \frac{x-a}{\sqrt{4 \alpha t^*}} \right) \right] \right]
\]

(2a)

for \( x \leq a \), and

\[
T(x, t) = \frac{A_v}{\rho c} \left[ t \left[ 2^2 \text{erfc} \left( \frac{x+a}{\sqrt{4 \alpha t}} \right) - 2^2 \text{erfc} \left( \frac{x-a}{\sqrt{4 \alpha t}} \right) \right] - H(t-t^*) (t-t^*) \left[ 2t^* \text{erfc} \left( \frac{x-a}{\sqrt{4 \alpha t^*}} \right) - 2t^* \text{erfc} \left( \frac{x+a}{\sqrt{4 \alpha t^*}} \right) \right] \right]
\]

(2b)

for \( x > a \), where \( t^* \) is the duration of heating (i.e., slip duration), \( \alpha \) is the thermal diffusivity, \( \rho \) and \( c \) are the bulk density and heat capacity, respectively. The \( \text{erfc}(\zeta) \) terms represent the second integral of the complementary error function evaluated from \( \zeta \) to \( \infty \) (Carslaw and Jaeger, 1959), and \( H(\zeta) \) is the Heaviside function.
which is evaluated for \( t = t^* \) indicating that the multiplied terms to the right are only applied when \( t \geq t^* \).

Eq. (2) shows that the frictional increase in temperature depends on slip duration \( (t^*) \), the half width of the slip zone \( (a) \), and heat generation rate \( (A_0) \), which is also a function of the average shear stress during slip \( (\tau) \) and slip magnitude \( (u) \) (Eq. (1)). Within the context of understanding earthquake and tsunami hazards, the parameters of most interest are the average shear stress during slip and slip magnitude. The average shear stress on faults during slip is one of the least constrained parameters in understanding and modeling the dynamics of earthquake rupture, whereas the magnitude of shallow slip has a strong influence on tsunami genesis. Many studies of frictional heating on faults use estimates of frictional heat generation to infer the shear stress during slip, assuming a value of total slip or slip rate (Eq. (1)) (e.g., Lachenbruch and Sass, 1980; O’Hara, 2004; Kano et al., 2006; Polissar et al., 2011). Alternatively, fault zone drilling provides access to fault rocks, and friction experiments can be used to estimate an upper bound on the average shear stress during slip based on the coefficients of low-speed friction for the fault, \( \mu_f \) and country rock, \( \mu_c \), and the fault zone orientation relative to the maximum principle stress direction.

Before interpreting the geologic signature of frictional heating, it is first important to characterize how frictional heating within a finite thickness slip zone affects temperatures as a function of slip zone thickness and slip duration. Fig. 2A shows the temperature response from a single frictional heating event as a function of time and space. In this example, the heat generation rate and duration of slip are 13.4 MW m\(^{-3}\) and 100 s, respectively. In Sections 3 and 4, we show that this temperature distribution is consistent with the vitrinite reflectance results of Sakaguchi et al. (2011) and that the heat generation rate corresponds with 49.2 m of slip along the Nankai megaslab at 271 mbfs assuming the laboratory-measured low-speed friction coefficient for this fault of 0.36 (Ikari and Saffer, 2011). Consistent with data obtained from the Nankai drill sites we use the following values for material parameters representative of the shallow subduction zone: \( \rho=2000 \text{ kg m}^{-3} \) (Kinoshita et al., 2009), \( c=1749 \text{ J kg}^{-1} \text{ K}^{-1} \) (Hirono et al., 2009), and \( \alpha=3.77 \times 10^{-7} \text{ m}^{2} \text{ s}^{-1} \) based on a thermal conductivity of 1.32 W m\(^{-1}\) K\(^{-1}\) (Kinoshita et al., 2009; Harris et al., 2011).

The red lines in Fig. 2A represent the temperature rise during slip \( (t \leq t^*) \) where frictional heat is generated throughout the slip zone. During slip temperatures within the fault zone rise dramatically and in this example reach peak values of 395 °C. The maximum temperature at any position within the slip zone occurs when \( t=t^* \) and peaks in the center \( (x=0) \). The solid black lines represent times after slip has completed \( (t > t^*) \) and show how the fault zone cools and the surrounding host rock heats through diffusion. The maximum temperature at locations outside the slip zone occurs at times greater than \( t^* \) as a function of the thermal time constants controlled by the thermal diffusivity.

We emphasize several points in Fig. 2A that we come back to when discussing the vitrinite reflectance data. First, because of diffusion and the finite time of fault slip the fault zone is not isothermal during heating despite constant frictional heat generation throughout the slip zone. Secondly, when the slip durations are short relative to the characteristic diffusion length, \( \sqrt{4\alpha t^*} \), as in this example, the majority of heat and therefore temperature rise during slip remain concentrated within the slip zone. Thinner slip zones or longer slip durations enhance the diffusive effects on the peak temperature during slip (Eq. (2)). Thus, thinner slip zones and longer durations require larger values of total heat generation \( A_0 t^* \) to achieve the same maximum peak temperature (Eqs. (1) and (2)). Finally, the maximum anomalous temperature at the edge of the slip zone is 50% of the peak anomalous temperature at \( x=0 \) when the characteristic diffusion length, \( \sqrt{4\alpha t^*} \), is greater than 1.5 times the half-width of the slip zone, \( a \). For a reasonable earthquake slip duration of 100 s, this relationship holds for slip zones that are more than several centimeters thick. For thinner slip zones and longer slip durations where \( \alpha/\sqrt{4\alpha t^*} < \sim 1.5 \), the maximum anomalous
temperature at the slip zone edge is greater than 50% of the maximum peak temperature. In these scenarios the diffusion front makes its way to the center of the slip zone during the slip/heating event, thereby inhibiting the peak temperature rise at \( x=0 \). For a thermal diffusivity of \( 3.7 \times 10^{-7} \, \text{m}^2 \, \text{s}^{-1} \) and a slip duration of 100 s, the maximum temperature at the slip zone edge is 50.2% of the maximum peak temperature anomaly for a half width of 2 cm, and 55.6% and 92.9% for 1 cm and 1 mm slip zone half-widths, respectively. These results highlight the importance of slip zone thickness and slip duration on temperature as a function of time and space. For different values of \( A_o, a, \) and \( t^* \), the resulting peak temperatures and temperature history will be different and can result in different geologic signatures, such as those recorded by vitrinite reflectance.

2.2. Vitrinite reflectance

Vitrinite is a coal maceral with a glassy appearance derived diagenetically from woody plant material. The random mean reflectance of vitrinite, \( R_o \), can be measured petrographically on thin sections under an oil immersion microscope. This value has been shown to be related to the extent of reaction, \( F \), by the empirical relationship (Sweeney and Burnham, 1990),

\[
R_o = (e^{-1.6 + 3.7F}),
\]

where \( F \) is controlled by a series of first-order Arrhenius kinetics (i.e., temperature-dependant reaction rates) that describe the parallel chemical reactions associated with the process of vitrinite thermal maturation (Sweeney and Burnham, 1990). Values of \( R_o \) from vitrinite macerals within sedimentary rocks are thus representative of the degree of thermal maturation resulting from the rock's temperature–time history. Because vitrinite reflectance is highly sensitive to peak temperatures and unaffected by retrograde reactions it is a good geothermometer that has been used to constrain the signature of frictional heating both within natural fault zones (Bustin, 1983; O'Hara, 2004; Suchy et al., 1997; Sakaguchi et al., 2007; Sakaguchi et al., 2011) and in laboratory shear experiments (O'Hara et al., 2006). Similar to previous studies on the effects of frictional heating (O'Hara, 2004; Polissar et al., 2011; Sakaguchi et al., 2007; 2011) we calculate simulated \( R_o \) values from given time–temperature paths based on the chemical kinetics model of Sweeney and Burnham (1990) to quantify the effects of different frictional heating scenarios.

Fig. 2B shows the expected response in \( R_o \) based on the frictional heating example in Fig. 2A. Changes in \( R_o \) depend in a complex way on the magnitude and duration of exposure to anomalous temperatures and to the initial background \( R_o \) value. Large temperature increases on the order of hundreds of degrees may change \( R_o \) significantly and smaller temperature increases may be maintained for considerable time with little to no effect on \( R_o \). For the frictional heating example in Fig. 2A, typical of the scenarios examined in this study, changes in \( R_o \) are most significant near the end of slip and for a short period afterwards when temperatures are largest (Fig. 2B). For the first 50 s of slip, \( R_o \) values remain unchanged and then increase dramatically in the last 50 s of slip when temperatures are hundreds of degrees above background (red curves). After slip has completed \( (t^* > 100 \, \text{s}) \), \( R_o \) values continue to rise, with large changes occurring within the first hundred seconds after slip but then slowing substantially after that. Within a thinner slip zone the peak temperature reduces more quickly and the post-slip impact on \( R_o \) is less. As discussed further in Section 3, temperatures in this example are not hot enough for long enough to significantly affect \( R_o \) values outside of the slip zone.

3. Modeling the Nankai data

3.1. Observations

Sakaguchi et al. (2011) analyze IODP cores from the Nankai Subduction Zone (Fig. 1) and map the random mean vitrinite reflectance \( (R_o) \) using a technique that allows the spatial distribution of \( R_o \) values to be measured within thin sections on very small grains. They find anomalous values in a 40 mm wide zone symmetrically distributed around the megasplay fault at 271 mbsf. Centered within this zone is a 20 mm band of darkened material. Similarly, for the frontal thrust at 438 mbsf they determine a 20 mm wide zone of anomalous \( R_o \) values centered on a 2 mm wide dark zone. In both faults, \( R_o \) values are greatest within the center of the darkened zone and diminish with distance away from it. The mean peak \( R_o \) values are 0.57 and 0.37 for the megasplay and frontal thrust, respectively, and are significantly higher than background values of roughly 0.24 and 0.27 in the surrounding material. Sakaguchi et al. (2011) suggest that the dark zones represent slip zones and that the anomalous values extending an additional \( \sim 1 \, \text{cm} \) to each side result from frictional heat diffusing into them during a slip duration of 100 s, the characteristic diffusion time for heat to diffuse \( \sim 1 \, \text{cm} \). Using a model for a temperature rise and subsequent diffusion within the center of the slip zone combined with the chemical kinetics for vitrinite, they interpret peak temperatures resulting from a slip duration of 100 s of 390 ± 50 and 330 ± 50 °C for the megasplay and frontal thrust, respectively. Because these values are hundreds of degrees larger than the temperatures expected from forearc geothermal gradients and present-day temperatures of 13 and 20 °C at these depths (Kinoshita et al., 2009; Harris et al., 2011), these findings are interpreted to suggest that both faults slipped coseismically.

In contrast to the results of Sakaguchi et al. (2011), Hirono et al. (2009) report analysis of other temperature proxies (fluid-mobile trace element concentrations, Sr isotopes, magnetic minerals, inorganic carbon content, and Raman spectra of carbonaceous material) on the dark zone material from the megasplay. These analyses do not reveal anomalous values within the inferred slip zone, leading Hirono et al. (2009) to suggest temperatures did not exceed 300 °C and that the fault may not have slipped with high velocity.

3.2. Models

We build on the analysis of the Nankai vitrinite reflectance data to evaluate the range of realistic frictional heating scenarios that can explain both the peak and the spatial distribution in anomalous \( R_o \) values. We assume a reasonable range of slip durations and two different scenarios for slip zone thickness: a “thin fault” scenario in which the thickness of the slip zone corresponds to the thickness of the darkened zone (dz), as hypothesized by Sakaguchi et al. (2011), and a “thick fault” scenario where the slip zone thickness corresponds to the full extent of the zone with anomalous \( R_o \) values (az). The “thick fault” scenario helps illustrate the sensitivity of the results to the estimates of slip zone thickness.

For both of the Nankai fault zones, we start with an initial burial history that results in the observed background values of \( R_o \) and present day temperature (Sakaguchi et al., 2011; Harris et al., 2011) and then evaluate the \( R_o \) response from frictional heating and diffusion. For different combinations of the slip duration and slip zone thickness, we use a predictor–corrector scheme to find the optimal value of \( A_o \) that results in the observed peak \( R_o \) in the center of the slip zone for each Nankai fault.
In addition to evaluating the effects of a single earthquake (i.e., frictional heating event), we also evaluate the cumulative effects of numerous events on \( R_o \) values. Our recurrence intervals are long enough that the thermal effects of the preceding earthquake are completely diffused away. With several possible scenarios for explaining the peak \( R_o \) depending upon \( t^* \), \( a \), and number of earthquakes, we use the spatial extent of anomalous \( R_o \) to assess whether additional aspects of the observations are able to place constraints on the range of plausible scenarios.

### 3.3. Results

Fig. 3 shows simulated \( R_o \) results for both the megasplay and frontal thrust for “thin fault” and “thick fault” scenarios in which the thickness of the slip zone is assumed to correspond to the thickness of the darkened zone (\( dz \)) or the full extent of the zone with anomalous \( R_o \) values (\( az \)), respectively. Results for the megasplay are in panel A and the frontal thrust in panel B. All of the results match the observed mean center peak \( R_o \) values reported by Sakaguchi et al. (2011). The colored curves represent different slip durations characterizing coseismic slip. Solid lines correspond to a single earthquake creating the peak \( R_o \) value and dashed lines correspond to the extreme scenario in which the peak \( R_o \) value results from the cumulative effect of 10,000 earthquakes. These results show that the spatial distribution in \( R_o \) is sensitive to the slip width but relatively insensitive to the number of large slip events when fitting the peak value with slip durations between 10 and 100 s.

Our results suggest that for reasonable slip durations associated with coseismic slip, anomalous \( R_o \) values do not extend significantly outside of the slip zone. Greater heat generation rates during coseismic slip could allow \( R_o \) to extend beyond the slip zone, but would result in peak \( R_o \) values larger than observed. However, assuming a slip duration of 100 s and a single heating event, temperatures resulting from the thin fault scenario that would allow anomalous \( R_o \) values to extend to full width of the observations would require peak \( R_o \) values of 3.47 and 4.67 for the megasplay and frontal thrust faults, respectively. These peak \( R_o \) values are more than five times greater than the observed peak values. We suggest that if slip was coseismic, the width of the slip zone would need to be larger than currently interpreted in order to explain the width of the anomalous \( R_o \) values.

Alternatively, slip durations considerably longer than 100 s are required for a thin slip model consistent with the \( R_o \) data. As described in Section 2.1, thin slip zones coupled with long duration slip can result in large temperatures significantly extending beyond the slip zone. We investigate this scenario assuming a slip duration of \( 10^3 \) s (Fig. 4). This slip duration corresponds to \( \sim 17 \) min, considerably longer than typical coseismic slip, but may be consistent with rapid afterslip or less likely with a shallow slow slip earthquake. In contrast to coseismic slip scenarios, these longer slip duration realizations are consistent with both the peak and the spatial extent of the \( R_o \) data. As before, the \( R_o \) distribution is relatively insensitive to the cumulative number of earthquakes used to achieve the peak value, although scenarios incorporating multiple events result in lower estimates of the characteristic heat generation rate \( A_o \) per event.

Fig. 5 shows observed \( R_o \) values (Sakaguchi et al., 2011) compared with computed \( R_o \) values based on the models presented in Figs. 3 and 4. The comparison suggests that the thick fault scenarios do a better job at explaining the width of the anomalous zone defined by Sakaguchi et al. (2011) unless the slip duration is very large (\( \sim 10^4 \) s). However, if the interpretations of a thin slip zone defined by the dark zone are correct (i.e., thin fault scenario) and the spatial extent of anomalous values is defined entirely by heat diffusion then these results suggest a large slip duration on the order of several minutes. Although our model scenarios try to match the statistical mean peak \( R_o \) and the...
interpreted width of the anomalous zone reported by Sakaguchi et al. (2011), it is obvious that considerable scatter exists in the data and estimating model parameters to better than an order of magnitude is not warranted. The source of scatter is not clear and may be a result of the rapid heating and thermal maturation process or discontinuous distribution of shear strain. We note that it may be possible that the spatial extent of anomalous $R_o$ is affected by translation of grains out of the slip zone into the surroundings during slip that effectively widens the spatial extent beyond that expected by heating alone and may also affect the spatial scatter. The potential for this process and its influence, if any, is not well understood.

The results of these thermal models provide estimates of the heat generation rate, $A_{\text{in}}$, in terms of slip duration, slip zone thickness, and number of earthquakes. Our analysis suggests that in both the megasplay and frontal thrust faults the anomalous $R_o$ values extend over the width of the slip zone and that the thick fault scenarios are most consistent with the data assuming coseismic slip durations on the order of $10$–$100$ s, although this implies a thicker slip zone than currently inferred. If the darkened zones reported by Sakaguchi et al. (2011) represent the slip zone (thin fault model), then slip durations are likely on the order of at least $\sim 10^3$ s. The spatial distribution in $R_o$ values is not sensitive to the total number of slip events.

4. Additional constraints and implications for coseismic slip

We examine the implications of these model scenarios in terms of peak temperature and characteristic slip per event. Eq. (1) yields an estimate of the characteristic slip magnitude per event from combinations of slip duration, slip zone thickness, and number of earthquakes if we can also reliably estimate the average shear stress during slip. We use low-speed friction data from fault zone rocks collocated with the vitrinite reflectance data (Ikari and Saffer, 2011) to place an upper bound on $\tau$,

$$\tau = \frac{1}{2} \left[ \left( \frac{M_1}{M_2} + 1 \right) - \left( \frac{M_1}{M_2} - 1 \right) \cos^2 \theta \right] \mu_c (1 - \lambda) \rho g z,$$

where $\theta$ is the angle between the maximum principal stress and the fault plane and $\lambda$ is the fluid pressure ratio, $\mu_c g z$. $M_1$ and $M_2$ are the stresses and $\mu_c$, defined by (adapted from Lachenbruch and McGarr, 1990),

$$M_1 = \left( 1 + \frac{\mu_c}{1 + \rho \mu_c} \right),$$

$$M_2 = \left( 1 - \frac{\mu_c}{1 + \rho \mu_c} \right).$$

For the Nankai faults, we assume a hydrostatic value of $\lambda=0.5$ for the fluid pressure ratio, $\theta$ values of 18.2° (Hirono et al., 2009) and 7.8° (Kimura et al., 2007) and $\mu_c$ values of 0.36 and 0.32 for the megasplay and frontal thrust, respectively, and a value of $\mu_c$ of 0.46 based on measurements from core samples from these same faults and surrounding country rock (Ikari and Saffer, 2011). Table 1 reports the results of our Nankai models in terms of the estimated slip and the resulting simulated peak temperature for each scenario. All scenarios match the peak $R_o$ value for each fault. Scenarios that also explain the spatial extent of anomalous $R_o$ values as described in Section 3.3 are indicated with bold boxes. Although the spatial distribution of $R_o$ is insensitive to the number of earthquakes when fitting the peak value, Table 1 shows that as larger numbers of earthquakes are used to the explain the peak $R_o$ value, both the characteristic slip per event and peak temperature are reduced (Figs. 6 and 7A). For example, Table 1 shows that to match the peak $R_o$ values with a thick fault for the megasplay, a slip duration of $10$ s requires slip of $48$ m for a single event and yields a peak temperature of $387$ °C. Repeated events decrease the characteristic slip per event and the corresponding peak temperatures so that with $10^4$ earthquakes the characteristic slip is $30.6$ m and the peak temperature is $252$ °C. The peak temperatures and slip per event are generally of similar magnitude when the slip duration is either $10$ or $100$ s. For slip durations more representative of rapid afterslip ($t^* = 1000$ s), the required slip magnitudes are greater and peak temperatures smaller. The relatively larger slip magnitude in the rapid afterslip scenarios ($t^* = 1000$ s) is likely a temperature compensation effect for the loss of heat due to diffusion as a result of the greater slip duration.

The “thin fault” scenarios consistent with the observed dark zones require smaller slip magnitudes than the thick fault scenarios and generate higher peak temperatures but fail to explain the width of the $R_o$ anomaly unless large slip durations are invoked (Table 1). In thin slip zones, the peak temperature and slip magnitude are more sensitive to slip duration than the thick

Fig. 5. Comparison between observed vitrinite reflectance ($R_o$) data (Sakaguchi et al., 2011) and simulated $R_o$ values for “thin” and “thick” fault scenarios in which the slip zone corresponds to the width of the darkened zone ($dz$) or the width of the zone with anomalous values ($a_z$). Scenarios are shown based on parameters for the megasplay (A) and frontal thrust (B) and for the effects of just one earthquake. Resulting departures from background values are generally confined to within the assumed slip zone thickness. Different colors reflect different slip duration ($t^*$) scenarios. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1 reports the results of our Nankai models in terms of the estimated slip and the resulting simulated peak temperature for each scenario. All scenarios match the peak $R_o$ value for each fault. Scenarios that also explain the spatial extent of anomalous $R_o$ values as described in Section 3.3 are indicated with bold boxes. Although the spatial distribution of $R_o$ is insensitive to the number of earthquakes when fitting the peak value, Table 1 shows that as larger numbers of earthquakes are used to the explain the peak $R_o$ value, both the characteristic slip per event and peak temperature are reduced (Figs. 6 and 7A). For example, Table 1 shows that to match the peak $R_o$ values with a thick fault for the megasplay, a slip duration of $10$ s requires slip of $48$ m for a single event and yields a peak temperature of $387$ °C. Repeated events decrease the characteristic slip per event and the corresponding peak temperatures so that with $10^4$ earthquakes the characteristic slip is $30.6$ m and the peak temperature is $252$ °C. The peak temperatures and slip per event are generally of similar magnitude when the slip duration is either $10$ or $100$ s. For slip durations more representative of rapid afterslip ($t^* = 1000$ s), the required slip magnitudes are greater and peak temperatures smaller. The relatively larger slip magnitude in the rapid afterslip scenarios ($t^* = 1000$ s) is likely a temperature compensation effect for the loss of heat due to diffusion as a result of the greater slip duration.

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Table 1
Slip required to match peak $R_o$ and the resulting peak temperature.

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* Slip derived from frictional heat source $A_s$, assuming $\mu_t = 0.36$ for the Megasplay (MS) and $\mu_t = 0.32$ for the frontal thrust (FT) (Ikari and Saffer, 2011); results with alternative friction coefficients are shown in Fig. 7B. Scenarios that explain both the peak and spatial extent of $R_o$ values are surrounded with bold values. Scenarios that also result in peak temperatures < 300 °C within the megasplay as constrained by Hirono et al. (2009) are in bold italic values.

slip zone models. This observation stems from the results described in Section 2.1; although diffusion has a greater effect during slip within thinner slip zones and require somewhat larger $A_s$ values to achieve the same temperature as a thicker slip zone, Eq. (1) shows that the required slip is linearly related to the slip zone thickness. Thus, for the same or somewhat similar $A_s$ value, smaller values of slip zone thickness $(2a)$ require smaller values of slip.

Fig. 7A illustrates the relationship between slip per event, slip duration, and number of earthquakes and graphically shows some of the relationships evident in Table 1 for thin slip zone scenarios. For these scenarios, differences in characteristic slip magnitude per earthquake are approximately linearly related to the base 10 logarithm of the number of earthquakes. The thick fault scenarios have larger estimates of slip and follow similar trends (Table 1). As noted above, differences in event parameters between slip durations of 10 and 100 s are small, whereas event parameters change markedly for slip durations of 1000 s. Fig. 7A also shows that as slip durations increase to periods longer than 1000 s the estimates of slip per event tend toward unrealistic values. Although peak temperature estimates are comparable between the two fault zones for comparable scenarios (within ~40 °C), the greater amount of slip estimated by the megasplay is mainly due to its relatively wider slip zone rather than differences in $\mu_t$ or $\tau$ (Fig. 7A; Table 1); for the thick fault scenarios the megasplay has a half-width of 2 cm compared to 1 cm for the frontal thrust.

The peak temperature results given in Table 1 and illustrated in Fig. 6 provide a method for reconciling the interpretations of the vitrinite reflectance data, suggesting peak temperatures much greater than 300 °C (Sakaguchi et al., 2011) with the temperature proxy data for the megasplay that suggest peak temperatures did not exceed 300 °C (Hirono et al., 2009). Reconciliation of these results suggests that the $R_o$ values within the megasplay may be the result of the cumulative effects ~10² earthquakes or more. Table 1 highlights the scenarios in bold that match this criteria for the megasplay. Similar constraints for the frontal thrust are not presently available.

Combining the slip per event with the number of frontal thrust gives an estimate of the total slip along each fault. For $10^3$–$10^4$ earthquakes, the slip per event estimates are on the order of tens of meters and would thus require total offset of tens to hundreds of kilometers of slip along the slip zones, which is unrealistic. Alternatively, $\sim 10^2$ earthquakes could still account for peak temperatures < 300 °C with between 1 and 5 km of total offset on each slip zone. Thus, our preferred scenarios result from ~$10^2$ earthquakes/slip events over geologic time and are able to explain both the peak and the spatial extent of anomalous $R_o$ values and are consistent with the other geothermometry data. For the megasplay, this implies roughly 37 m of coseismic slip or roughly 43 m of rapid afterslip. For the frontal thrust this amounts to
slip per event are likely minimum values for several reasons. First, we assume that roughly all the dissipated energy from frictional work is converted to heat (e.g., Lachenbruch and Sass, 1980; Fulton and Rathbun, 2011). However, if a considerably large fraction of energy is consumed by making new surface area or by chemical reactions (e.g., Wilson et al., 2005; Hirono and Hamada, 2010) then a larger amount of work would need to be done to raise the temperature to levels required to explain the observations. Secondly, although the laboratory friction measurements show that the samples from both fault zones are velocity-strengthening (Ikari et al., 2009), the potential for dynamic weakening by thermal pressurization during rapid slip remains viable. Assuming a permeability of $<5.5 \times 10^{-20}$ m$^2$ based on core sample measurements from the megasplay (Ikari et al., 2009) and a bulk compressibility of $\sim 10^{-8}$ Pa$^{-1}$ based on values from other Nankai core samples (Bourlange et al., 2004), hydraulic diffusivity is estimated to be roughly 2 orders of magnitude less than the thermal diffusivity, implying that thermal pressurization is likely and that the effective friction coefficient during slip may be less than we assume (Mase and Smith, 1987). In this case estimates of slip would need to be increased to generate the same heat production or temperature required to explain the observations. Fig. 7B shows the slip per earthquake estimates for each fault assuming one earthquake for alternative coefficients of friction within the fault zone during slip for the thick fault scenarios. These transformations can be made for any scenario within Table 1 by multiplying the estimated slip by the $\mu_f$ (0.36 and 0.32 for the megasplay and frontal thrust, respectively) and then dividing by an alternative $\mu_f$ value.

Several processes could lead to an overprediction of heat generation and temperature from fault zone vitrinite reflectance data. As noted by Sakaguchi et al. (2011), vitrinite grains may have been transported along the fault plane from deeper depths. Even though this effect cannot be ruled out, we feel this scenario is unlikely as the grains would need to travel from considerable depth in order to significantly affect the estimates presented here, and would need to be confined to a very thin zone. However, as noted above, it may be possible that lateral translation of grains out of the slip zone during slip potentially influences the overall spatial extent and scatter of anomalous values. Secondly, our models would be overpredicted if the anomalous $R_o$ zone width reflected the cumulative history of numerous closely spaced slip zones. Because of the very small spatial extent of even our “thick fault” scenarios and the overall shape of the anomaly, we also consider this explanation unlikely. We note that even in the “thick fault” scenarios large coseismic slip is still estimated for both the megasplay and frontal thrust (Table 1). Finally, our thermal models are purely conductive and do not account for the possibility of advective fluid flow. Model results from Fulton et al. (2010) suggest large permeability values $>10^{-14}$ m$^2$ are required for advection to affect fault zone temperature soon after an earthquake. For fluid advection to have caused the anomalous vitrinite reflectance values alone without frictional heating, rapidly moving fluids would likely need to be on the order of more than 100 °C greater than the surrounding country rock and confined to just within a very narrow zone. Although further investigation is warranted, we consider the likelihood of this scenario to be small.

Lastly, we emphasize that although the kinetics model of Sweeney and Burnham (1990) is often used to interpret signatures of frictional heating recorded in vitrinite reflectance, this model is derived from, and specifically calibrated for, natural and laboratory data with heating rates on the order of several degrees over a period of hours to tens of millions of years. Faster heating rates associated with earthquake slip (e.g., several tens to hundreds of degrees per second) may require different kinetic parameters and functions that may

roughly 12.5–14.3 m of coseismic slip or roughly 21.5 m of rapid afterslip.

5. Discussion

If the kinetics model of Sweeney and Burnham (1990) is appropriate for frictional heating, our estimates of characteristic
influence estimates of temperature. Our estimates of slip assume that the observed anomalous $R_o$ values are due entirely to frictional heating. Anomalous $R_o$ values may also result from the effects shear strain (Ross and Bustin, 1990; Mastalerz et al., 1993; Wilks et al., 1993). The experimental data of Mastalerz et al. (1993) suggest this effect may only be significant at temperatures $>350 \, ^\circ\text{C}$ above the range of our preferred scenarios, but these experiments were focused on relatively slow strain rates (e.g., $10^{-2} - 10^{-3}$). High strain rate may mechanochemically induce a change in the molecular structure of organic matter and/or result in vitrinite reflectance kinetics. The potential for non-thermal effects on vitrinite reflectance due to rapid fault slip remains largely unconstrained and experimental work is needed to better characterize and understand these effects.

Overall, model parameters consistent with the vitrinite reflectance data predict large peak temperature and extremely large slip magnitudes and very large total displacement for these shallow positions. The peak temperatures are inconsistent with the results of Hirono et al. (2009) unless the vitrinite reflectance data result from a great many earthquakes and unrealistic total displacements. The slip magnitudes are only comparable to the March 2011 $M_w$ 9.0 Tohoku earthquake of northern Japan which is estimated to have had more than 50 m of surface rupture based on repeat bathymetry (Fujiwara et al., 2011), teleseismic inversions (Lay et al., 2011), and changes in survey location of seafloor seismometers and pressure sensors (Ito et al., 2011). If our modeled slip magnitudes are correct for Nankai, these results suggest both the megasplay and the frontal thrust faults also hosted slip associated with M$\sim$9 earthquakes (e.g., Kanamori and Brodsky, 2004). Longer slip durations such as that possibly associated with creep events or afterslip does not help because these scenarios also require large slip and Brodsky and Mori (2007) show that creep events and aftserslip less than the earthquakes generating them. To our knowledge, there is no other evidence suggesting such a large megathrust earthquake along the Nankai trough in the geologic past. Even if the kinetics model of Sweeney and Burnham (1990) leads to an overestimate of fault slip parameters, the vitrinite reflectance data nevertheless suggest that conceptual models of the updip limit of the seismogenic zone should be re-evaluated (Sakaguchi et al., 2011). While we do not discount the possible hazard for these faults, we suggest instead that the large estimates of slip and total geologic displacement over time imply that our current understanding of how vitrinite reflectance is affected by rapid fault slip and associated frictional heating is flawed. In order for more accurate and confident analysis of earthquake slip parameters from fault zone vitrinite reflectance data, work is needed to better determine the chemical kinetics suited for fast heating rate conditions and investigate the possible influence of non-thermal effects on $R_o$ values during rapid fault slip, such as the effects of shear strain and/or strain rate.

6. Conclusions

Using a comprehensive thermal model for frictional heat generation and diffusion within a finite thickness slip zone coupled with the thermal kinetics of vitrinite maturation, we find that the spatial distribution of vitrinite reflectance $R_o$ is relatively insensitive to the number of earthquakes or a range of reasonable coseismic slip durations when fitting the peak value. For coseismic slip durations, we find that the spatial distribution in anomalous $R_o$ is sensitive to the slip zone thickness ($2\alpha$).

Vitrinite reflectance data (Sakaguchi et al., 2011) coupled with the kinetics model of Sweeney and Burnham (1990) suggest large magnitudes of heat generation and peak temperatures. Interpreting the predicted heat generation in terms of frictional heating, and assuming conservative values of fault friction, leads to large peak temperatures ($>300 \, ^\circ\text{C}$) and slip magnitudes of several tens of meters. Coseismic slip durations imply the width of the slip zone corresponds to the width of the anomalous vitrinite reflectance values. Longer slip durations decrease peak temperatures, and relax the constraint that the slip zone corresponds to the width of the anomalous $R_o$ values, but still requires several tens of meters of slip, and implies the slip is not coseismic. The cumulative effects of a large number of repetitive earthquakes can explain the magnitude and distribution of $R_o$ values with modestly smaller estimates of peak temperatures and slip per earthquake, but require larger total displacements. Reconciliation of the peak temperature estimates from vitrinite reflectance data with other proxy estimates that imply maximum peak temperatures of no more than 300 $^\circ\text{C}$ based on inorganic geochemistry and magnetic mineral data, is possible with $\sim100$ or more earthquakes. However, the slip per event values are still very large and result in unrealistically large total displacement estimates. We caution that these very large values of slip may also reflect limitations in our understanding of how vitrinite reflectance is affected by rapid fault slip, which will require further investigation. Our results illustrate how integrating vitrinite reflectance data with careful modeling and other rock measurements holds the promise of constraining slip parameters from ancient earthquakes.

Acknowledgments

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