Paleomagnetism reveals the emplacement age of tsunamigenic coral boulders on Ishigaki Island, Japan

T. Sato[1], N. Nakamura[1,2], K. Goto[2], Y. Kumagai[1], H. Nagahama[1], and K. Minoura[1]
[1]Department of Earth Science, Tohoku University, 6-3 Aoba, Sendai 980-8578, Japan
[2]International Research Institute of Disaster Science, Tohoku University, 6-6-4 Aoba, Sendai 980-8579, Japan

ABSTRACT

We use temperature-dependent viscous remanent magnetization to estimate the emplacement age of tsunamigenic coral boulders along the shorelines of Ishigaki Island, Japan. The boulders consist of the hermatypic coral *Porites*, and the time of their deposition by tsunamis has been established using radiocarbon dating. Recently deceased corals at reef edges around Ishigaki Island record the Earth's current magnetic field (present Earth field, PEF) as a remanence parallel to the field in the skeleton. Since the time when the coral skeletons were emplaced on the shorelines as boulders by destructive tsunami waves, a new viscous magnetization was partially overprinted in the boulder parallel to the PEF. The results of thermal demagnetization indicated that the boulders were rotated at least once, and their emplacement ages determined from L. Néel's relaxation theory for single-domain magnetite agree well with the radiocarbon ages, although there are traces of multidomain magnetites. New application of Néel's theory to tsunamigenic coral boulders gives us an opportunity to ascertain the age and transportation mode of individual tsunamigenic coral boulders in this area.

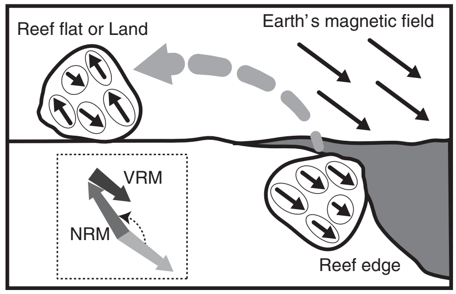

Figure 1. Conceptual illustration of emplacement of tsunamigenic coral boulder. Boulders originally grew as corals *Porites* on the reef edge or reef flat before the tsunami. The corals acquired depositional remanent magnetization parallel to Earth's current magnetic field as natural remanent magnetization (NRM). When broken by the tsunami, the corals were transported and emplaced on the reef flat or on land. Subsequently, with time, new remanence was superimposed as viscous remanent magnetization (VRM) parallel to Earth's current magnetic field.

INTRODUCTION

The presence of tsunamigenic boulders along shorelines provides an opportunity for reconstructing past tsunami events in the long-term geological record. Unraveling the history and recurrence of past tsunamis is an important task in creating risk-management policies (Bryant and Nott, 2001; Noormets et al., 2002; Frohlich et al., 2009). Because huge boulders (>10 t) are mainly transported by low-frequency, high-impact tsunami events (e.g., Goto et al., 2013; Hongo et al., 2012), although some boulders might be displaced by storm waves (e.g., Salzmann and Green 2012), it is important to reconstruct the timing of tsunamis and the transportation history of such boulders in order to mitigate the risk of future tsunami events. At Ishigaki Island along the Ryukyu Trench, Japan, Araoka et al. (2013) determined the radiocarbon ages of the youngest parts of ~90 coral boulders and revealed 8 peaks in the probability distribution of tsunami events during the past 2500 yr. However, radiocarbon dating is unable to determine whether subsequent tsunamis transported the boulders. Moreover, most tsunamigenic boulders are distributed along the coastline as individual boulders, such as in northeast Japan (Nandasena et al., 2013) and Tonga (Frohlich et al., 2009), and radiocarbon dating is not always applicable to all tsunami boulders (consisting of volcanic and sedimentary rocks). Therefore, an alternative dating method, with information on process, is required to overcome these problems.

Although cosmogenic nuclide exposure dating is a powerful tool for dating individual boulders (e.g., Mackey and Lamb, 2013), it provides no information about the past horizontal sliding motions of the boulders because the cosmogenic nuclides simply accumulate on the boulder surface. However, paleomagnetic viscous dating can be used to predict the transportation history and age of boulders regardless of the boulder lithology. If corals at Ishigaki Island are capable of recording a characteristic remanence parallel to the Earth's current magnetic field (present Earth field, PEF), post-tsunami coral boulders will overprint a new partial magnetization in the form of a temperature-dependent viscous remanent magnetization (VRM). At near-surface temperatures, rocks magnetize viscously when random thermal fluctuations cause some electron spin-moments to rotate until they align with the PEF. Thus, a new magnetization is progressively acquired with age. Although the magnetization of coral is considered to be very weak, if it is measureable, the VRM could be used to identify the timing and mode of recent rotations of coral boulders (Heller and Markert, 1973; Kent, 1985; Tyson-Smith and Verosub, 1994; Borradaile, 1996) (Fig. 1). The theoretical framework for understanding VRM originates with Néel (1949, 1955). Pullaiah et al. (1975) derived a time-temperature relation by assuming Néel's (1949, 1955) single-domain (SD) theory of magnetite. This provides a formula that SD-sized magnetite can acquire VRM in a field at low temperature, T_A, over a long relaxation time, t_A, and the VRM is demagnetized in a laboratory at high temperature, T_D, over a short relaxation time, t_D, given by

$$\frac{T_D \ln Ct_D}{J_s H_c} = \frac{T_A \ln Ct_A}{J_s H_c}, \quad (1)$$

where J_s is the saturation magnetization, H_c is coercivity, and C is a frequency factor with a value of 10^{10} Hz. For magnetite, one determines J_s variation with temperature, from thermomagnetic curves, and also H_c varies similarly with temperature. Therefore, we can replace the denominators in Equation 1 with J_s^2 (Pullaiah et al., 1975). The older remagnetized component in nature can be erased by the higher temperature in the laboratory, and the reverse for the younger component (Pullaiah et al., 1975; Borradaile, 1998). To employ this theory it must first be confirmed that the corals contain SD or fine-grained pseudo-SD magnetite. Tyson-Smith and Verosub (1994) succeeded in the application of the Pullaiah et al. (1975) nomograph to 800-yr-old landslide deposits with SD magnetite. The higher unblocking temperature yields an older age than that predicted by Néel's (1949, 1955) theory if there are coarser (multidomain, MD) magnetic grains in a sample (Walton, 1980; Middleton and Schmidt, 1982; Kent, 1985). In our study, paleomagnetic viscous dating is applied to individual tsunamigenic coral boulders found at Ishigaki Island, and the timing and transportation mode of tsunamis in the region are compared with previously obtained radiocarbon dates and the results of a field survey.

CHARACTERISTICS OF INDIVIDUAL TSUNAMIGENIC CORAL BOULDERS

The Ryukyu Islands are rimmed by fringing reefs. Large tsunamis pick up single-colony *Porites* and *Favia* directly from the reef moat and the reef edge, and deposit them on the shore

GEOLOGY, July 2014; v. 42; no. 7; p. 603–606; Data Repository item 2014212 | doi:10.1130/G35366.1 | Published online 22 May 2014

as boulders (see Fig. DR1 in the GSA Data Repository[1]). Field observations have confirmed that some boulders have been flipped upside down, based on the coral growth textures. Radiocarbon dating of these coral boulders has suggested that multiple tsunami events have occurred in this area at intervals of 150–400 yr (Araoka et al., 2013). The coral reefs at Ishigaki Island were formed later than 8500 calendar yr B.P. (Yamano et al., 2001; Hongo and Kayane, 2009). Our main study area was Miyara Bay (on the southeastern shoreline of the island), where many tsunamigenic boulders are distributed (Goto et al., 2010, 2013). Reef-flat corals *Scleractinia*, mainly consisting of *Porites* and *Favia* (Kato and Kimura, 1983), at Miyara Bay were sampled 400–1300 m away from the reef edge in March and September 2012 (Fig. 2).

High-temperature hysteresis properties show that the remanent magnetization and coercivity reduced to ~580 °C (Fig. DR2), suggesting that the origin of the remanence carrier is stoichiometric magnetite, although the room-temperature hysteresis parameters of M_r/M_i (~2.4) and H_{cr}/H_c (~3.6) suggest a mixture of SD and MD magnetite (Dunlop, 2002). Standard oriented paleomagnetic core samples were drilled in geographical coordinates and were thoroughly washed in distilled water under ultrasonication to remove fouling. Grayish coral samples, not the ivory color typical of coral skeletons, could be measured using a fluxgate spinner magnetometer (Aspin; Natsuhara Giken Co. Ltd., Osaka, Japan) with a sensitivity of 5×10^{-6} m Am^2. A low-temperature demagnetization (LTD) technique (e.g., Ozima et al., 1964) was then applied three times in order to remove the soft component from any coarse-grained magnetite present, decreasing the remanence to no less than 85% (average 95%) of its natural remanence after the LTD technique. This suggests that very little coarse-grained (MD) magnetite was present. Stepwise thermal demagnetization was performed to trace the low-coercivity VRM component using a thermal demagnetizer (TDF-98; Natsuhara Giken Co. Ltd., Osaka, Japan) under precise temperature control (<±1 °C). A low rate of temperature increase was used (low cutback and low output values), in order to avoid temperature overshoot. The Lowrie-Fuller (1971) test, X-ray diffraction analysis, and scanning surface stray magnetic-field measurements were also applied to grayish and ivory-colored coral skeletons to determine the approximate grain size of the magnetic minerals (see the Data Repository). These rock magnetic results confirmed that the remanence carriers in the samples were of SD or pseudo-SD magnetite, so it can be assumed that the Néel (1949, 1955) relaxation theory for viscous remanence was approximately valid.

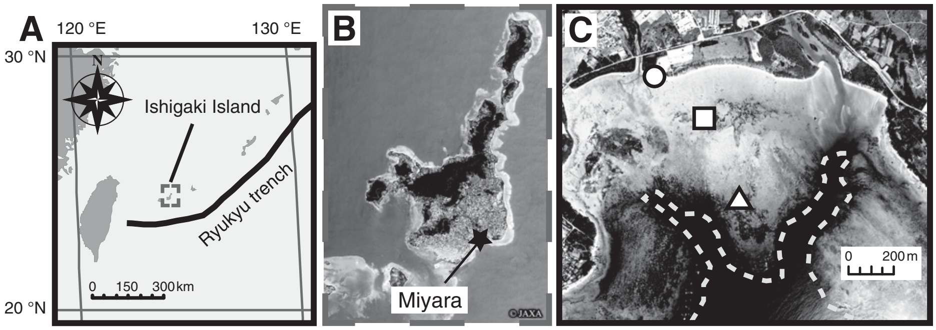

Figure 2. A: Map showing location of Ishigaki Island along the Ryukyu Trench in the southwestern part of Japan, drawn using ArcGIS software (ESRI Inc., www.esri.com). B: Satellite image of Ishigaki Island, provided by Japan Aerospace Exploration Agency (JAXA), showing location of Miyara Bay (black star). C: Aerial photograph of Miyara Bay area; reef is indicated by dashed line (provided by the Geospatial Information Authority of Japan). Triangle indicates location of dead coral near the reef edge that was used as a reference sample. Circle indicates a tsunamigenic coral boulder emplaced by the A.D. 1771 Meiwa tsunami (boulder KK). Square shows one of the largest (200 t) boulders at Miyara Bay.

DETERMINING BOULDER ROTATION AND ITS AGE USING VRM COMPONENTS

The fact that the coral boulders had already been radiocarbon dated allowed our paleomagnetic dating results to be calibrated. To confirm that in-situ corals become magnetized parallel to the PEF, stepwise thermal demagnetization measurements were carried out on in-situ deceased and fossilized corals near the reef edges. As shown in Figures 3A and 3B, the results confirmed the parallelism. The parallelism allowed us to determine if the tsunamigenic boulders were flipped or displaced with respect to the reef edge. Here we show two successive examples of this application.

In the first experiment, stepwise thermal demagnetization was applied to a parallel piped tsunamigenic coral boulder with a weight of ~35 t, a length of ~4 m, and a height of ~3 m (referred to as boulder KK). The emplacement age for this boulder was determined to be A.D. 1771 (the Meiwa tsunami; Kato and Kimura, 1983). Using this radiocarbon age, we could calibrate the timing of the tsunami. Deceased coral from near the reef edge was first demagnetized from 80 to 400 °C in 20 °C increments with a duration of 300 s. However, because this temperature increment corresponds to several hundred years in the Pullaiah et al. (1975) unblocking nomogram, a precise age of the tsunami event could not be determined using paleomagnetic viscous dating. To obtain a more accurate estimate, a 5 °C increment was used for the demagnetization temperature range of 100–150 °C with a duration of 300 s. For 80 to 100 °C, and 150 to 200 °C, a 10 °C interval was used, and for 200 to 400 °C, a 50 °C interval was used. Figure 3C shows an example of the resulting vector component changes in a Zijderveld plot (see the Data Repository for alternating field demagnetization). The younger VRM component is subparallel to the PEF up to its unblocking temperature of 135 °C. The older component as a characteristic remanence direction is then isolated from the maximum temperature of 400 °C. As shown in the nomogram in Figure 4, an unblocking temperature of 135 °C corresponds to a paleomagnetic age of 1700 yr ago. This probably corresponds to the A.D. 1771 Meiwa tsunami event, although there is disagreement between the paleomagnetic and radiocarbon ages. The finer 2 °C thermal demagnetization increment prohibited the determination of the VRM turning point due to a zigzag and noisy demagnetization pattern. Nevertheless, the orientation of the older component was upward, which agrees well with the field observation of a downward direction for the coral growth pattern, suggesting flipping of the boulder.

Paleomagnetic viscous dating was next applied to one of the largest tsunamigenic boulders of coral *Porites* in Miyara Bay. It weighed ~200 t, and was roughly cylindrical with a diameter of 10 m and a height of ~3 m. Figure 3D shows the results of thermal demagnetization measurements on this boulder with a 5 °C increment. It can be seen that two characteristic VRM components are present, and that the youngest exhibits an unblocking temperature of 145 °C with a duration of 300 s. The radiocarbon age of this boulder has not yet been determined. The orientation of the older component shows an upward orientation, which agrees with field observations concerning the coral growth pattern. The fact that the younger component is not parallel to the PEF may be due to incomplete flipping of this boulder. Paleomagnetic viscous dating predicts an age of ca. 14 ka, which is not consistent with the frequency distribution range of radiocarbon ages determined by Araoka et al. (2013) (Fig. 4). Moreover, this age is too old to be associated with an acquisition of VRM in corals

[1]GSA Data Repository item 2014212, supplemental Figures DR1–DR7 and Table DR1 (low-temperature demagnetization data), is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

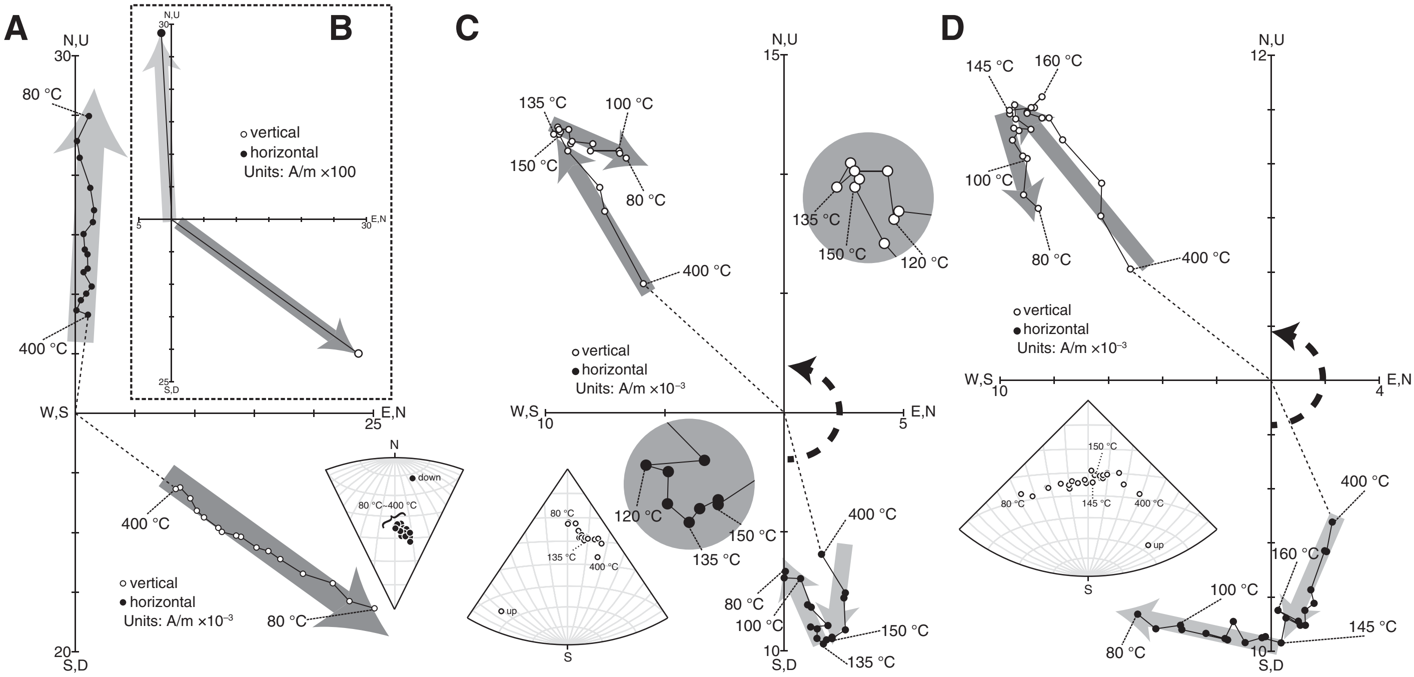

Figure 3. Vector plots for successive thermal demagnetization steps. A: In-situ dead and fossilized coral skeleton near the reef edge as a reference recorder of Earth's current magnetic field (present Earth field, PEF) at Ishigaki Island, Japan. U—up; D—down. Stereonet shows that all vector components point to same direction down. B: Vector plot for PEF measured by a fluxgate magnetometer. C: Example of vector component changes for the 35 t boulder (KK) emplaced by A.D. 1771 Meiwa tsunami. At unblocking temperature of 135 °C, high-temperature (older) and low-temperature (younger) components became isolated. Younger component is almost parallel to the PEF. In addition, the stereonet suggests the change in direction of magnetic components due to the historical reorientation. D: Results for the 200 t boulder (Miyara Bay), indicating an age older than that predicted by the Néel (1949, 1955) theory. The older and younger components become isolated at 145 °C. The younger component is subparallel to the PEF because of incomplete flipping of boulder.

because the present reefs were formed between 6000 and 5000 cal yr B.P. (Yamano et al., 2001). However, according to Hongo et al. (2012), such a huge boulder, with weight of ~200 t, could only be displaced by a large tsunami. Therefore, it is possible that the observed change in the magnetic vector component reflects a past tsunami event, the age of which cannot be determined. It is also possible that the Pullaiah et al. (1975) nomogram is not valid in this case because of the presence of coarser-grained magnetite.

We considered that the age difference between the ages determined by our paleomagnetic viscous dating and radiocarbon dating may be due to equipment problems of internal heat conduction and uneven heat duration. To investigate this, the internal temperature of several samples was measured using a type-K thermocouple in the center of the sample. We found that a uniform temperature gradient existed and that the sample's internal temperature was synchronized with the oven temperature, as determined by another platinum resistance thermocouple. Another possible source of error is that whereas experimental studies have shown that the Pullaiah et al. (1975) contours are valid for strictly SD assemblages, pseudo-SD and MD assemblages require higher unblocking temperatures to remove the equivalent VRM (Walton, 1980; Middleton and Schmidt, 1982; Dunlop and Özdemir, 2000; Dunlop, 2012). LTD results also showed that some of the boulders decrease their remanence after multiple LTD, suggesting that very little MD magnetite was present. There may be some memory even in MD grains after LTD. Therefore, the discrepancies in the ages may be the result of changes in grain size or domain configurations.

As described here, for the two boulders investigated in our study, the VRM exhibited a single turning point. However, the unblocking temperatures were different. The estimated age for the 200 t coral boulder in the center of the reef moat was considerably older than that for the 35 t boulder KK, which was emplaced further inland along the beach during the Meiwa tsunami (A.D. 1771) (see Fig. 2). This implies that the 200 t coral boulder was

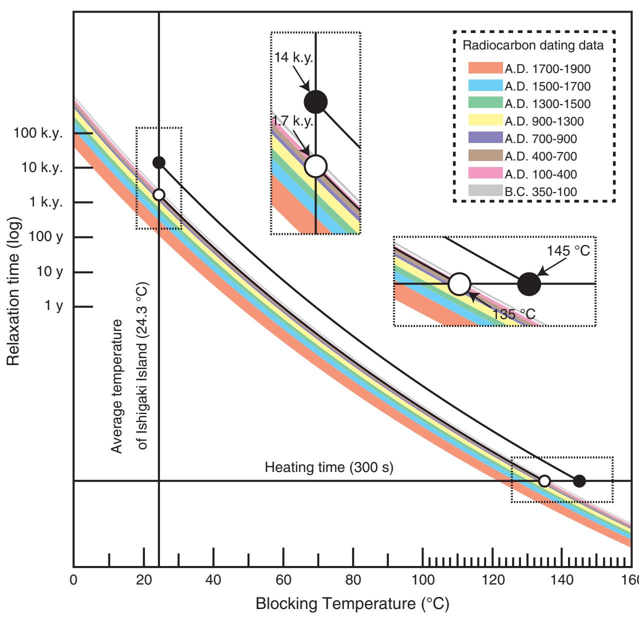

Figure 4. Pallaiah et al. (1975) nomogram for single-domain magnetite superimposed with radiocarbon dating of tsunamigenic coral boulders. Color scale indicates radiocarbon ages determined by Araoka et al. (2013). Black circles show turning points of paleomagnetic vector components at relaxation time of 300 s, and predicted age calculated using average annual temperature at Ishigaki Island, Japan (24.3 °C). White circles show the relationship between unblocking temperature at a relaxation time of 300 s and the calculated viscous dating age.

immobile when the Meiwa tsunami struck the island and moved the 35 t boulder KK over the 1.0-km-wide reef. This suggests that the earlier tsunami was larger than the Meiwa tsunami. Radiocarbon dating can only determine the age at which the coral died under the impact of the tsunami, but it cannot identify whether the older 200 t boulder was moved during the Meiwa tsunami. However, paleomagnetic viscous dating allows the motion of individual boulders, and the magnitude of past tsunamis in this region as a long-term geological process, to be constrained, although hydrodynamic tsunami simulations are required to settle this problem. A large number of tsunami boulders have been found along coastlines worldwide. However, few studies have used such boulders to elucidate the recurrence and magnitudes of ancient tsunamis (Araoka et al., 2013). Although this study tested the applicability of the paleomagnetic viscous dating to these boulders using corals, this application could work in any setting where the boulders have SD magnetic particles, regardless of boulder lithology, as an independent and alternative means of dating boulders. In combination with hydrodynamic tsunami simulations, it is believed that this application has the potential to reveal the magnitudes of multiple tsunamis from individual boulders.

CONCLUSIONS

Tsunamigenic coral boulders at Ishigaki Island were found to have VRM parallel to the PEF, and from their unblocking temperatures, the date of their emplacement by tsunamis could be predicted and compared with existing radiocarbon dates. Although precise magnetic mineralogy is required, this is a unique technique for revealing the transportation process, and for predicting ages using individual boulders, regardless of their lithology. A combination of this method and hydrodynamic tsunami simulations would be expected to make a substantial contribution to tsunami disaster mitigation.

ACKNOWLEDGMENTS

We are grateful to Minoru Funaki at the National Institute of Polar Research (Tokyo, Japan). We also thank Graham J. Borradaile for his critical reading of the manuscript and for improving our English grammar. This work was supported by the Japan Society for the Promotion of Science Grant-in-Aid for Scientific Research (B) (22340146) and a Grant-in-Aid for Priority Project Research of the International Research Institute of Disaster Science (C-12) (Tohoku University, Japan). Constructive comments from Editor James Spotila and three anonymous reviewers greatly improved the manuscript.

REFERENCES CITED

Araoka, D., Yokoyama, Y., Suzuki, A., Goto, K., Miyagi, K., Miyazawa, K., Matsuzaki, H., and Kawahata, H., 2013, Tsunami recurrence revealed by *Porites* coral boulders in the southern Ryukyu Islands, Japan: Geology, v. 41, p. 919–922, doi:10.1130/G34415.1.

Borradaile, G.J., 1996, An 1800-year archaeological experiment in remagnetization: Geophysical Research Letters, v. 23, p. 1585–1588, doi:10.1029/96GL01575.

Borradaile, G.J., 1998, Rock magnetic constrains on long-term cliff slump rates and coastal erosion: Geotechnique, v. 48, p. 271–279, doi:10.1680/geot.1998.48.2.271.

Bryant, E.A., and Nott, J., 2001, Geological indicators of large tsunami in Australia: Natural Hazards, v. 24, p. 231–249, doi:10.1023/A:1012034021063.

Dunlop, D.J., 2002, Theory and application of the Day plot (M_{rs}/M_s versus H_{cr}/H_c): 1. Theoretical curves and tests using titanomagnetite data: Journal of Geophysical Research, v. 107, no. B3, p. 1–22, doi:10.1029/2001JB000486.

Dunlop, D.J., 2012, Magnetic recording in rocks: Physics Today, v. 65, p. 31–40, doi:10.1063/PT.3.1604.

Dunlop, D.J., and Özdemir, Ö., 2000, Effect of grain size and domain state on thermal demagnetization tails: Geophysical Research Letters, v. 27, p. 1311–1314, doi:10.1029/1999GL008461.

Frohlich, C., Hornbach, H.J., Taylor, F.W., Shen, C.-C., Moala, A., Morton, A.E., and Kruger, J., 2009, Huge erratic boulders in Tonga deposited by a prehistoric tsunami: Geology, v. 37, p. 131–134, doi:10.1130/G25277A.1.

Goto, K., Shinozaki, T., Minoura, K., Okada, K., Sugawara, D., and Imamura, F., 2010, Distribution of boulders at Miyara Bay of Ishigaki Island, Japan: A flow characteristic indicator of tsunami and storm waves: The Island Arc, v. 19, p. 412–426, doi:10.1111/j.1440-1738.2010.00721.x.

Goto, K., Miyagi, K., and Imamura, F., 2013, Localized tsunamigenic earthquakes inferred from preferential distribution of coastal boulders on the Ryukyu Islands, Japan: Geology, v. 41, p. 1139–1142, doi:10.1130/G34823.1.

Heller, F., and Markert, H., 1973, The age of viscous remanent magnetization of Hadrian's Wall (northern England): Geophysical Journal International, v. 31, p. 395–406, doi:10.1111/j.1365-246X.1973.tb06510.x.

Hongo, C., and Kayane, H., 2009, Holocene coral reef development under windward and leeward locations at Ishigaki Island, Ryukyu Islands, Japan: Sedimentary Geology, v. 214, p. 62–73, doi:10.1016/j.sedgeo.2008.01.011.

Hongo, C., Kawamata, H., and Goto, K., 2012, Catastrophic impact of typhoon waves on coral communities in the Ryukyu Islands under global warming: Journal of Geophysical Research, v. 117, G02029, doi:10.1029/2011JG001902.

Kato, Y., and Kimura, M., 1983, Age and origin of so-called "tsunami-ishi", Ishigaki Island, Okinawa prefecture: Geological Society of Japan Journal, v. 89, p. 471–474, doi:10.5575/geosoc.89.471 (Japanese with English abstract).

Kent, D.V., 1985, Thermoviscous remagnetization in some Appalachian limestones: Geophysical Research Letters, v. 12, p. 805–808, doi:10.1029/GL012i012p00805.

Lowrie, W., and Fuller, M., 1971, On the alternating field demagnetization characteristics of multidomain thermoremanent magnetization in magnetite: Journal of Geophysical Research, v. 76, p. 6339–6349, doi:10.1029/JB076i026p06339.

Mackey, B.H., and Lamb, M.P., 2013, Deciphering boulder mobility and erosion from cosmogenic nuclide exposure dating: Journal of Geophysical Research, v. 118, p. 184–197, doi:10.1002/jgrf.20035.

Middleton, M.F., and Schmidt, P.W., 1982, Paleothermomemory of the Sydney basin: Journal of Geophysical Research, v. 87, p. 5351–5359, doi:10.1029/JB087iB07p05351.

Nandasena, N.A.K., Tanaka, N., Sasaki, Y., and Osada, M., 2013, Boulder transport by the 2011 Great East Japan tsunami: Comprehensive field observations and whither model predictions?: Marine Geology, v. 346, p. 292–309, doi:10.1016/j.margeo.2013.09.015.

Néel, L., 1949, Theorie du trainage magnetique des ferromagnetiques au grains fins avec applications aux terres cuites: Journal de Physique et le Radium, v. 5, p. 99–136.

Néel, L., 1955, Some theoretical aspects of rock magnetism: Advances in Physics, v. 4, p. 191–243, doi:10.1080/00018735500101204.

Noormets, R., Felton, E.A., and Crook, K.A.W., 2002, Sedimentology of rocky shorelines: 2 Shoreline megaclasts on the north shore of Oahu, Hawaii—Origins and history: Sedimentary Geology, v. 150, p. 31–45, doi:10.1016/S0037-0738(01)00266-4.

Ozima, M., Ozima, M., and Nagata, T., 1964, Low-temperature treatment as an effective means of "magnetic cleaning" of natural remanent magnetization: Journal of Geomagnetism and Geoelectricity, v. 16, p. 37–40.

Pullaiah, G., Irving, E., Buchan, K.I., and Dunlop, D.J., 1975, Magnetization changes caused by burial and uplift: Earth and Planetary Science Letters, v. 28, p. 133–143, doi:10.1016/0012-821X(75)90221-6.

Salzmann, L., and Green, A., 2012, Boulder emplacement on a tectonically stable, wave-dominated coastline, Mission Rocks, northern KwaZulu-Natal, South Africa: Marine Geology, v. 323–325, p. 96–106, doi:10.1016/j.margeo.2012.07.001.

Tyson-Smith, R., and Verosub, K.L., 1994, Thermoviscous remanent magnetism of Columbia River Basalt blocks in the Cascade landslide: Geophysical Research Letters, v. 21, p. 2661–2664, doi:10.1029/94GL02669.

Walton, D., 1980, Time-temperature relations in the magnetization of assemblies of single-domain grains: Nature, v. 286, p. 245–247, doi:10.1038/286245a0.

Yamano, H., Kayane, H., and Yonekura, N., 2001, Anatomy of a modern coral reef flat: A recorder of storms and uplift in the late Holocene: Journal of Sedimentary Research, v. 71, p. 295–304, doi:10.1306/082900710295.

Manuscript received 10 December 2013
Revised manuscript received 18 April 2014
Manuscript accepted 22 April 2014

Printed in USA