UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

August 1, 1997

Dr. Stephan Brocoum
Assistant Manager for Licensing
U. S. Department of Energy
Office of Civilian Radioactive Waste Management
P. O. Box 30307
Las Vegas, NV 89036-0307

SUBJECT: U.S. DEPARTMENT OF ENERGY RESPONSES TO IGNEOUS ACTIVITY TECHNICAL EXCHANGE OPEN ITEMS (BROCOUM TO GREEVES 6/4/97)

Dear Dr. Brocoum:

Thank you for your letter of June 4, 1997, which describes: (1) the U.S. Department of Energy's (DOE's) approach to update the results of the Probabilistic Volcanic Hazard Assessment (PVHA) expert elicitation, when and if new, pertinent information becomes available, and (2) how DOE will use the results of the PVHA expert elicitation to treat igneous activity in its Total System Performance Assessment supporting the 1998 Viability Assessment (TSPA-VA). The U.S. Nuclear Regulatory Commission staff has reviewed the letter and considers that it fulfills DOE's commitment specified in Agreement 8 of the DOE/NRC Technical Exchange of February 25-26, 1997. As agreed, NRC will consider this information when preparing the NRC Issue Resolution Status Report (IRSR) on Igneous Activity. Specific comments on the two topics addressed in your letter follow:

o **Evaluation of New Data:** Enclosure 1 of your letter describes, as agreed, through an example, how DOE would approach updating the results of the PVHA expert elicitation as new data becomes available. This approach consists of assessing the implications of "new data" primarily through sensitivity analysis and determining the impact of the new data relative to its effect on the probability density functions (PDF). If there is a significant change, particularly in the mean value of the distribution, the new data would ther be considered significant, and the effects on risk would be evaluated. In general, staff considers t' at such a process is adequate, with the recognition that in some cases all of the geological implications may not be apparent from a pure statistical analysis and, therefore, will require requisite geological expertise be involved in the process. However, we do have an interest in what mechanism in the proposed process assures that DOE is routinely considering the implications of new data collected not only by DOE, but also outside the project, as it becomes available.

  Your letter noted that more information on DOE's process for the evaluation of new data will be forthcoming in a letter being prepared to address Site Characterization Analysis open item 3. The staff will review this letter to gain additional understanding of this process.

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- **Use of PDF for Probability of Disruption and the Treatment of Consequences in TSPA-VA:** Enclosure 2 of your letter responds to the agreement reached at the Technical Exchange. "DOE agrees to explain how the PDF for the probability of disruption will be used in performance assessment, including sensitivity studies,...." We find the approach described generally acceptable; however, as discussed at the recent Technical Exchange July 21-22, 1997, the anticipated result of the sensitivity studies might be achieved more simply and efficiently. NRC's review of the igneous aspects of the TSPA-VA will focus on DOE's analysis of direct disruption. NRC's independent modeling, which will be part of that review, will assume an annual frequency of 10^{-7}, which is included in your alternative model 2 .

  To date, staff has done little work on indirect or secondary effects. While we recognize the U.S. Environmental Protection Agency has not proposed a standard, for a risk-based or dose-based standard, these effects will probably change only the timing of peak dose and, therefore, may be generally inconsequential in evaluating total risk. In this regard, the staff is also very much interested in the analyses described under Point 5 of the Treatment of Consequences of Direct and Indirect Magmatic Events in TSPA-VA in Enclosure 2 of your letter. In this vein, enclosed is a "pre-print" of a soon-to-be published paper by Conner, et al., *Cooling of an Igneous Dike Twenty Years After Intrusion*, Geology (In Press) that provides potentially useful information for these analyses.

  A technical exchange addressing, among other topics, how DOE will treat the igneous disruptive scenarios in its TSPA-VA is scheduled for October 1997. At that meeting, we would like to discuss at length the approach outlined in Enclosure 2. In the meantime, we would like to be informed if this approach changes.

Your letter requested a copy of the Tephra Dispersion model that has been developed by the Center for Nuclear Waste Regulatory Analyses. A copy of the code, along with a report containing the technical description and users guide, has been sent to you under separate cover.

Finally, your letter indicates that DOE believes that the probability subissue is closed. As we recently informed you in our letter of June 24, 1997, staff considers that certain aspects of the volcanic probability subissue can be closed at the staff level. The significance of the secondary and indirect events is still being evaluated by NRC. As discussed above, if these processes and events are estimated to have little effect on the value of total risk, additional aspects of this subissue can be closed at the staff level. The status of issue resolution related to the probability of volcanism, as well as our rationale, will be documented in the forthcoming IRSR on Igneous Activity, planned to be issued in the Fall of 1997.

In closing, we thank you again for your letter. While staff does not consider that all aspects of igneous events have been resolved, we do feel that considerable progress has been made. A written response to the above is not required. If you have any questions regarding this letter, please contact me at (301) 415-7252 or Dr. John Trapp at (301) 415-8063.

Sincerely,

Original Signed By:

Newton K. Stablein, Acting Branch Chief
Engineering and Geosciences Branch
Division of Waste Management
Office of Nuclear Material Safety
and Safeguards

Enclosure: As stated

cc: See attached list

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ENCLOSURE

Cooling Of An Igneous Dike 20 yr After Intrusion

C. B. Connor

P. C. Lichtner

F. M. Conway

B. E. Hill

Center for Nuclear Waste Regulatory Analyses, Southwest Research Institute, San Antonio, Texas, 78238

A. A. Ovsyannikov

I. Federchenko

Yu. Doubik

V. N. Shapar

Institute of Volcanic Geology and Geochemistry, Petropavlovsk-Kamchatskii, Russia

Yu. A. Taran

Intituto de Geofisica, Universidad Nacional Autonoma de Mexico, 04510, Mexico D.F., Mexico

ABSTRACT

The 1975 Tolbachik, Kamchatka, Russia, eruption resulted in the formation of three basaltic cinder cones. During this eruption, shallow dike injection into a nearby cinder cone, Cone 1004, caused deformation and slumping of the cone. In 1995, temperatures at 2 m depth, electromagnetic anomalies, and geologic units were mapped on the slump block. These data reveal details about the cooling rates of a shallow dike in the slump block, including: (1) measured temperatures up to 475 °C; (2) temperatures greater than 200 °C along a 160-m-long and 30-m-wide zone that trends oblique to bedding; (3) a low resistivity zone at 80 m depth that may delimit a larger intrusion beneath the shallow dike; (4) a dry zone extending 15-20 m from the axis of the

thermal anomaly; and (5) a condensation zone beyond this dry-out zone, characterized by steaming ground and high convective heat flux. Analytic models indicate that the surprisingly high temperatures persist because of the low thermal diffusivity of the scoria into which the dike is injected, a direct result of the scoria's high porosity. Two-phase nonisothermal flow models suggest that the observed patterns of dry-out and condensation are expected for small volume fractions of water in the scoria (≤10%). Thus, field observations from Tolbachik provide a graphic example of the roles of rock thermophysical properties and water in the unsaturated zone on rates of dike cooling.

INTRODUCTION

One-dimensional transient heat conduction models have been used to show that dike cooling is a rapid process, essentially complete after a few months or years in the case of a large dike (e.g., McBirney, 1984; Delaney, 1987). The great Tolbachik fissure eruption, Kamchatka, Russia, occurred in 1975 and resulted in the formation of three closely spaced cinder cones and eruption of 0.45 km^3 (dense rock equivalent) of basalt. Igneous dikes and dike segments intruded to extremely shallow depths during the eruption, sometimes hundreds of meters from active vents. This remarkable geologic event provides an unique opportunity to measure the surface thermal anomalies produced by dikes twenty years after their injection, and to observe patterns in water vapor convection and the extent of dry-out zones surrounding the dike associated with these thermal anomalies.

Observations at the Tolbachik cinder cones elucidate the complexity of dike cooling in the natural environment. At Tolbachik, these complexities include significant variation in the thermo-physical properties of rock, the presence of a deeper, larger intrusion, the development of dry-out zones around the dike which potentially limit alteration despite long cooling times, and other perturbations in water saturation in the rock surrounding the dike intrusion. Observations from Tolbachik are used to evaluate the relative importance of these complicating factors using numerical models that consider the thermo-physical rock properties and two-phase transport of water in the unsaturated zone, in addition to simple heat conduction (Lichtner, 1996; Seth and Lichtner, 1996).

The cinder cones formed during the Tolbachik eruption created a north-trending alignment. These three cones and their associated lava flows erupted between July and September, 1975 (Magus'kin et al., 1983; Doubik et al., 1995). The three cinder cones extend an alignment that includes three older (Holocene) cinder cones that are south of the 1975 cones. The northernmost of these Holocene cinder cones is Cone 1004. A period of dike injection during the eruption of the first of the 1975 cones, Cone I, resulted in deformation of Cone 1004. This deformation was manifest in the slow uplift and lateral sliding of a coherent block of Cone 1004 scoria during a period of several days in late July and August, 1975, forming a east-northeast-trending valley between the slump block and Cone 1004 that is ~ 240 m long and 100 m wide (Fig. 1). Pit craters opened at the base of Cone I and along the axis of the valley during deformation. This activity was followed by the formation of a lava vent, 285 m from the base of Cone I, slightly offset from the axis of the valley (Fig. 1). This vent is at an elevation 45 m below the current floor of the valley. By 31 July, the lava flows issuing from the vent were more than 1 km long.

MEASURED TEMPERATURES OF A COOLING DIKE

Ground temperatures on the Cone 1004 slump block were mapped in July and August, 1995. This was accomplished by measuring temperatures at depths of 1.75–2.0 m, using 2-m-long probes and ungrounded chromel-alumel thermocouples. Probes were allowed to equilibrate in thermal areas for 1-2 hr. Measurements were made at 310 stations on the slump block, concentrating on one 160-m-long and 50-m-wide thermal zone (Figure 1). Ground temperatures outside of thermal areas were typically 0-23 °C. Temperatures within the thermal zone were as high as 475 °C. The scoria at the surface over the thermal zone is typically 100-120 °C and remains dry during rain. Small patches of steaming ground occur 20-30 m upslope from the axis of the thermal anomaly; during rainfall these patches grow in area and emit steam.

The thermal anomaly at Cone 1004 is interpreted to be produced by a shallow cooling igneous dike because of its high temperature, the elongated narrow shape of the anomaly, its relationship to the lava vent southwest of the slump block, and because the anomaly trends oblique to bedding exposed in the slump block. A similar high temperature zone was identified on the slopes of Cone 1004 and is also inferred to be a dike, although this thermal anomaly was not mapped in detail.

Electromagnetic (EM) soundings were made to investigate the character of the thermal anomaly at greater depths. Dry or nearly dry scoria has an infinite resistivity (> 10, 000 Ωm) except when heated to temperatures in excess of 600 °C. Above 600 °C the resistivity of basalt is 1-10 Ωm (Rai and Manghnani, 1977; Kauahikaua et al., 1986). EM stations (24) were occupied on the Cone 1004 slump block using a large-loop source. The results indicate that a region of very low resistivity exists at depths of ~ 80-300 m beneath the valley that separates the slump block from Cone 1004 (Fig. 1). This EM anomaly is interpreted to indicate the position of a volume of rock heated to about 600 °C. The depth of this low-resistivity anomaly correlates well with the elevation of the lava vent (Fig. 1), and this supports the interpretation that the anomaly is produced by a basalt intrusion larger than the mapped extent of the surface thermal anomaly. The presence of this more voluminous intrusion explains the tremendous deformation associated with the formation of the slump block. Thus, the surface thermal anomalies are related to a shallow dike that intruded the scoria above this more voluminous intrusion.

MODELS OF DIKE COOLING

Surface temperature data alone are not sufficient to uniquely constrain geometry. For example, numerous factors, such as change in dike width or depth, or even change in the porosity of scoria surrounding the dike, could account for the temperature variation observed along the axis of the thermal anomaly. Nonetheless, thermal models can be used to explore the relative importance of several factors that may contribute to the extended period of cooling of the shallow dike in the slump block. These factors include: (1) a difference in bulk thermal conductivities of the dike and the scoria it intrudes; (2) heat transfer into the dike from a more voluminous intrusion at depth, as detected by the EM survey; and (3) low heat transfer between the scoria and the atmosphere. Dike cooling was modeled and compared to observations from Tolbachik to explore the sensitivity of cooling rates to these factors.

The effect of differences in thermal conductivities between the dike and scoria on temperature can be investigated using a one-dimensional transient conduction model:

$$[\rho_f C_f \phi + \rho_r C_r (1-\phi)] \frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial x^2} ,$$

where T is the rock temperature at time t and distance x within the rock of density ρ_r, porosity ϕ, specific heat C_r, and bulk thermal conductivity, κ. The terms ρ_f and C_f refer to the density and specific heat of the pore fluid (e.g., air, water vapor, or water), respectively, and are negligible in scoria with low liquid saturation. This equation assumes that heat conduction occurs through the rock matrix and that pore fluids are in thermal equilibrium with the rock matrix.

Bulk thermal conductivity, κ, is strongly affected by porosity. Several models have been developed to estimate the effect of changing porositv on bulk thermal conductivity (e.g., Somerton, 1958; Bailsford and Major, 1964), each of which makes assumptions about the connectivity of pore spaces and the shapes of individual grains. Changing thermal conductivity in a basalt with increasing porosity and air filling the pore space is graphed in Figure 2 using four different models. The thermal conductivity of basalt with no porosity is assumed to be 2 W/m °C and the thermal conductivity of air to be 0.05 W/m °C. In the scoria of Cone 1004, the basalt clasts are nonwelded, inflated, poorly sorted, and typical porosity is 40%-60%. On the basis of the four models (Figure 2), the thermal conductivity of the 1004 scoria is 0.1-0.5 W/m °C. Because the scoria fragments are angular, rather than spherical as assumed in some of the models, the true bulk thermal conductivity is likely closer to the minimum of this range.

Temperature and saturation also affect bulk thermal conductivity. However, the thermal conductivities of water ($\kappa = 0.5$ W/m °C at 100 °C) and steam ($\kappa = 0.03$ W/m °C at 100 °C) are low compared to dense basalt. Thus, in partially saturated scoria (e.g., < 0.2 volume fraction liquid), porosity has the largest influence on bulk thermal conductivity.

Field measurements were also made to determine the bulk thermal conductivity of the Cone 1004 scoria, using the shallow temperature gradient, measured between 10 cm and 2 m depths, and heat flux, measured by a micro-foil heat flux sensor anchored to an aluminum plate. Bulk conductivity is estimated from these data by application of Fourier's Law.

Measured bulk thermal conductivity varies in the vicinity of the thermal anomaly, but is minimum and most consistent in the zone of highest temperature gradient near the axis of the thermal anomaly. For measurements made in the highest temperature zone, thermal conductivity of the scoria is 0.21±0.07 W/m °C (Fig. 2). In cooler areas (30-100 °C), typically 15-40 m from the axis of the thermal anomaly, apparent bulk thermal conductivity was between 1 and 5 W/m °C. These very high values measured in cooler areas are not true measures of bulk thermal conductivity. This is because significant convective heat transfer occurs due to the circulation and condensation of water vapor in these areas, resulting in high measured heat flux. Therefore, measurements made using the heat flux sensor also provide a way of mapping the lateral extent of dry-out away from the cooling dike.

Field measurements of bulk thermal conductivity in the highest temperature zone are in good agreement with models κ_{min} and κ_{mg} (Fig. 2) of the decrease in bulk thermal conductivity as a function of porosity. The scoria in the dike zone has a bulk thermal conductivity of ~ 0.2 W/m °C, about one order of magnitude less than that of dense basalt. Field measurements of bulk thermal conductivity also indicate that a dry-out zone extends ~ 15-20 m from the axis of the thermal anomaly.

An analytical solution for one-dimensional time-transient heat conduction is achieved using a Laplace Transform (Carslaw, 1921; Ozisik, 1980). The dike is treated as a finite homogeneous body in perfect thermal contact with the scoria, treated as a semi-infinite region. Representative thermo-physical properties for the dike and scoria are given in Table 1.

Varying scoria porosity from 20% to 50% strongly affects rates of dike cooling by conduction. For example, 20 yr after the intrusion of a 5-m-wide dike, maximum temperatures vary between 250-440 °C with this range of scoria porosity (Fig. 3). In contrast, welded ignimbrite that is assumed to have the same thermo-physical properties as the dike (Table 1) cools to ~100 °C at the dike contact after 20 yr.

Numerical two-dimensional modeling of heat conduction by finite differences was used to model expected temperatures within the slump block 20 yr after intrusion for comparison with observations. In this model the surface temperature is held to 10 °C, insulating boundary conditions are used at the dike centerline and far from the dike, and a no heat flux boundary is used at a depth of 80 m. Temperatures measured at approximately 1.85 m depth in the hottest, widest part of the anomaly are plotted and compared with calculated results (Fig.4). For a 10-m-wide dike buried at 10 m depth, the calculated temperature at 1.85 m depth and 20 yr after intrusion is cool compared to observations. Rather, measured temperatures correspond well to temperatures expected at about 6.5 m beneath the surface (3.5 m above the dike in this calculation). This temperature difference suggests that upward flow of air, water vapor, and pore gases creating a boundary layer at the surface which partially accounts for the high temperatures observed near the surface. Vertical temperature profiles between the surface and 2-m-depth show a changing temperature gradient in the scoria (Fig. 5). These temperature gradients are much more easily explained by convective heating of the scoria above the cooling dike than by a pure conduction model.

A constant heat source was used at the base of the dike in some models to simulate the cooling intrusion indicated by the EM anomaly. This model suggests that conduction of heat vertically along the dike from an intrusion at 80 m depth has negligible influence on near-surface temperature. Proceeding at a rate proportional to the diffusion length $\sqrt{\alpha t}$, heat transfer away from the dike near the surface after 20 yr is not greatly affected by heat transfer from the larger intrusion at depth.

Although water does not strongly affect rates of conduction in the scoria, the presence of even a small amount of water in the unsaturated zone may have an effect on rates of dike cooling when convection is considered. The theoretical basis for models of thermally driven redistribution of moisture in the unsaturated zone, and the effects of moisture on rates of cooling, were discussed in Tsang and Pruess (1987) and Buscheck and Nitao (1993). The MULTIFLO computer code (Lichtner, 1996; Seth and Lichtner, 1996) was used to model the change in water content within the unsaturated zone in response to dike injection, using various initial volume fractions of liquid water. MULTIFLO solves conservation equations for mass and energy in time and space for a nonisothermal two-phase system. Darcy's law, combined with binary diffusion in the gas phase, is used to compute liquid and gas fluxes in the scoria and dike. Heat flow takes place by conduction through the solid portions of the dike and scoria, or by convection of water and water vapor through the pore spaces in the scoria and fractures in the dike.

Application of the MULTIFLO model in one dimension suggests that a 5-m-wide dike will be ~ 100 °C cooler 20 yr after the dike is emplaced in scoria, if the scoria initially contains an average of 10% water and cools by conduction and convection, rather than cooling by pure conduction only (Fig. 6; cf. 50% porosity curve in Fig. 3). High-temperature gradients near the dike create a dry zone within which the volume fraction of water is zero. In the case of 0.1 initial volume fraction of water, the dry zone is 20 m wide after 20 yr of cooling of the 5-m-wide dike, in good agreement with our observations at Tolbachik. Ground water is vaporizing beyond the dry zone. Vaporization of ground water results in flow of liquid water and water vapor away from the dike. This water vapor cools and condenses between 20 and 60 m from the dike. As a result, the volume fraction of water increases within this zone and temperature is near 100 °C (Fig. 6). This configuration will persist until the dike cools and the dry zone collapses. We have not modeled convective heat transfer in two-dimensions. However, we infer from the one-dimensional model that gravity drainage of liquid water and buoyant rise of water vapor in and near the condensation zone likely sets up fluid flow about the cooling dike.

CONCLUSIONS

Field observations on the Cone 1004 slump block provide empirical evidence that rates of dike cooling are significantly affected by the thermophysical properties of the dike and scoria it intrudes. At Cone 1004, the low bulk thermal conductivity of the scoria limits heat flux from the dike, prolonging cooling. On the basis of the rates of cooling over the last 20 yr, this dike will require at least 100 yr to cool below 100 °C. Temperature gradients and heat flux measurements, coupled with numerical analyses, suggest that convective heat transfer also plays a significant role in the redistribution of heat about the dike, leading to the develop of condensation zones adjacent to the dike and convective heat flow above the dike.

ACKNOWLEDGMENTS

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REFERENCE CITED

Bailsford, A. D. and Major, K. G., 1964, The thermal conductivity of aggregates of several phases, including porous materials: British Journal of Applied Physics, v. 15, p. 313-319.

Buscheck, T. A., and Nitao, J. J., 1993, The analysis of repository-heat-driven hydrothermal flow at Yucca Mountain, *in* Proceedings, Site Characterization and Model Validation, Focus '93: LaGrange Park, IL, American Nuclear Society, p. 127-144.

Carslaw, H. S., 1921, Introduction to the mathematical theory of conduction of heat in solids, (second edition): London, United Kingdom, MacMillian and Co., 268 p.

Delaney, P. T., 1987, Heat transfer during emplacement and cooling of mafic dykes, *in* Halls, H.C., and Fahrig, W. F., eds., mafic dyke swarms: Geological Association of Canada Special Paper 34, p. 31-46.

Doubik, Y., Ovsyannikov, A. A., Connor, C. B., Martin, R., and Doubik, P., 1995, Development of the 1975 Tolbachik cinder cone alignment - Nature of areal and lateral basaltic volcanism: Eos (Transactions, American Geophysical Union), v. 76, p. F540.

Fedotov, S., Balesta, S. T., Dvigalo, V. N., Razina, A. A., Flerov, G. B., and Chirkov, A. M., 1991, New Tolbachik volcanoes, *in* Fedotov, S., and Masurenko, Y. P., eds., Active volcanoes of Kamchatka: Moscow, Nauka Publishers, p. 275-279.

Kauahikaua, A. J., Jackson, D. B., and Zablocki, C. J., 1986, Resistivity structure at a depth of 5 km beneath Kilauea volcano, Hawaii from large-loop-source electromagnetic measurements (0.04-8 Hz): Journal of Geophysical Research, v. 91, p. 8267-8283.

Lichtner, P. C., 1996, Continuum formulation of multicomponent-multiphase reactive transport, *in* P. C. Lichtner et al., eds., Reactive transport in porous media: Reviews in Mineralogy v. 34, p. 1-81.

Magus'kin, M. A., Enman, V. B., and Tselishchev, V. S., 1983, Changes in the height, volume, and shape of the new Tolbachik volcanoes of the Northern Breakthrough, *in* Fedotov, S. A., and Markinin, Ye. K., eds., The great Tolbachik fissure eruption, 1975-1976: Cambridge, Massachusetts, Cambridge University Press, p. 307-315.

McBirney, A. R., 1984, Igneous petrology: San Francisco, California, Freeman Cooper, 504 p.

Ozisik, M. N., 1980, Heat Conduction: New York, John Wiley and Sons, 687 p.

Rai, M. P., and Manghnami, M. H., 1977, Electrical conductivity of basalts to 1,550 °C, in Dick, H., ed., Magma genesis (Proceedings of the American Geophysical Union Chapman Conference on Partial Melting in the Earth's Upper Mantle): Oregon Department of Geology and Mineralogy Bulletin, v. 96, p. 219-232.

Seth, M. S., and Lichtner, P. C., 1996, User's manual for MULTIFLO: Part 1, Metra, 1.0, Two-phase nonisothermal flow simulator: San Antonio, Texas, Center for Nuclear Waste Regulatory Analyses, CNWRA96-005, 53 p.

Somerton, W. H., 1958, Some thermal characteristics of porous rocks: Journal of Petroleum Technology, v. AIME 2008, p. 61-64.

Tsang, Y. W., and Pruess, K., 1987, A study of thermally induced convection near a high-level nuclear waste repository in partially saturated fractured tuff: Water Resources Research, v. 23, p. 1958-1966.

Figure Captions

Figure 1. Tolbachik cinder cones I-III (modified from Fedotov et al.(1991)) are located on the Kamchatka peninsula. A: First lava flow of the eruption (Cone I lava) erupted from lava vent southwest of Cone I, preceded by slumping on north side of Cone 1004. B: Anomalous temperatures (>200°C) mapped on the slump block occur within 30-m-wide and 160-m-long zone. C: Electromagnetic soundings (EM, 24) are interpreted in terms of depth (m) to low resistivity zone. Topographic contour interval on the temperature and EM maps is 5 m.

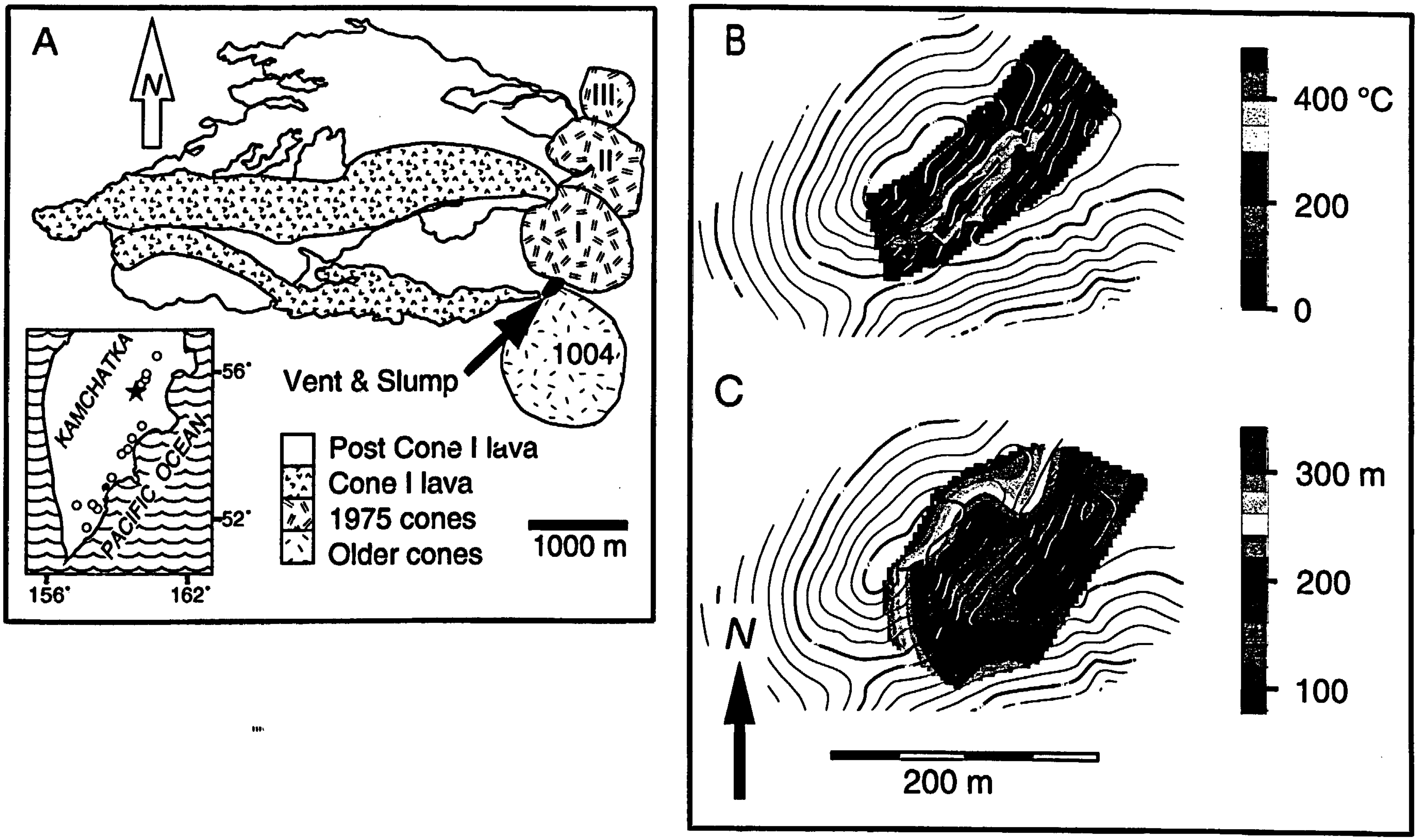
Figure 2. Strong dependence of bulk thermal conductivity on porosity for basalt in unsaturated zone is estimated using κ_{max} (maximum possible thermal conductivity), κ_{min} (minimum possible thermal conductivity), κ_{mg} (expected geometric mean thermal conductivity), and κ_{m} (thermal conductivity estimated using Maxwell's relation). Box indicates range of thermal conductivity based on temperature gradient and heat flux data collected in dry-out zone.

Figure 3. Cooling history is dependent on thermo-physical properties of rock intruded. Here, expected temperatures are shown for 5-m-wide dike 20 yr after intrusion, calculated using one-dimensional time transient conduction model varying scoria porosity from 20%-50% (see Table 1). In contrast, dike in welded ignimbrite cools much faster.

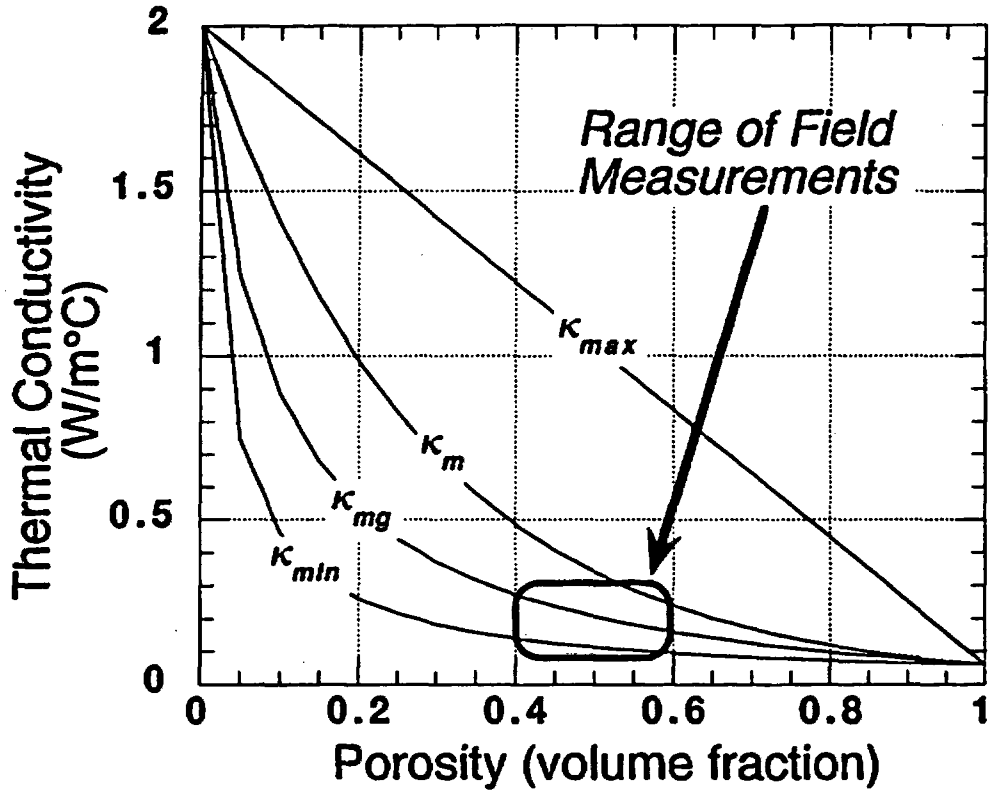
Figure 4. Observed temperatures at 1.85 m depth (symbols) across hottest part of thermal anomaly. Expected temperature profile at 1.85 m and 6.5 m depth 20 yr after intrusion of a 10-m-wide dike at 10 m depth (solid lines). Expected temperatures based on two-dimensional pure conduction model.

Figure 5. Near-surface vertical temperature gradients measured at four locations within the thermal anomaly.

Figure 6. Water in unsaturated zone is redistributed during dike cooling: 20 yr after injection of 5-m-wide dike into scoria with 10% initial saturation, dry-out zone extends 15-20 m from dike contact. Condensation zone develops from 20 to 60 m , within which saturation nearly doubles and temperature is buffered at ~ 100 °C. For these conditions, dike cools slightly faster than indicated by pure conduction model with 50% porosity (see Fig. 3).

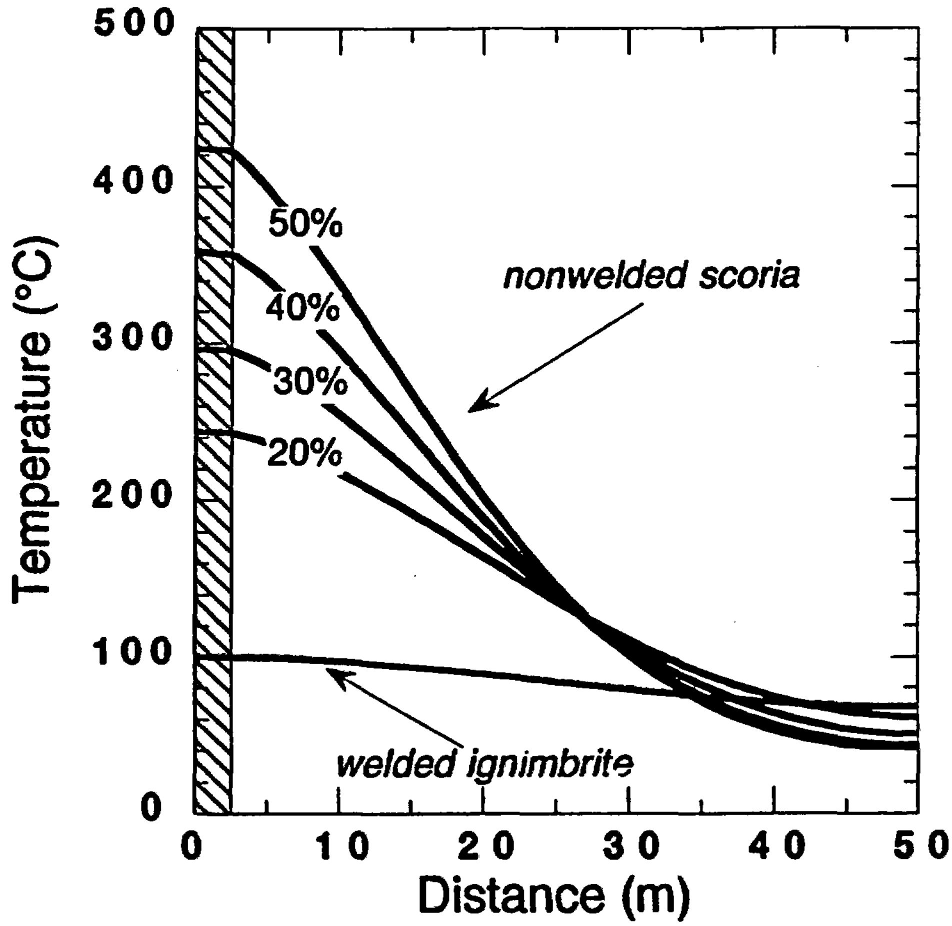


A
N
III
II
I
1004
Vent & Slump
KAMCHATKA
PACIFIC OCEAN
56°
52°
156°
162°
Post Cone I lava
Cone I lava
1975 cones
Older cones
1000 m
B
400 °C
200
0
C
300 m
200
100
N
200 m

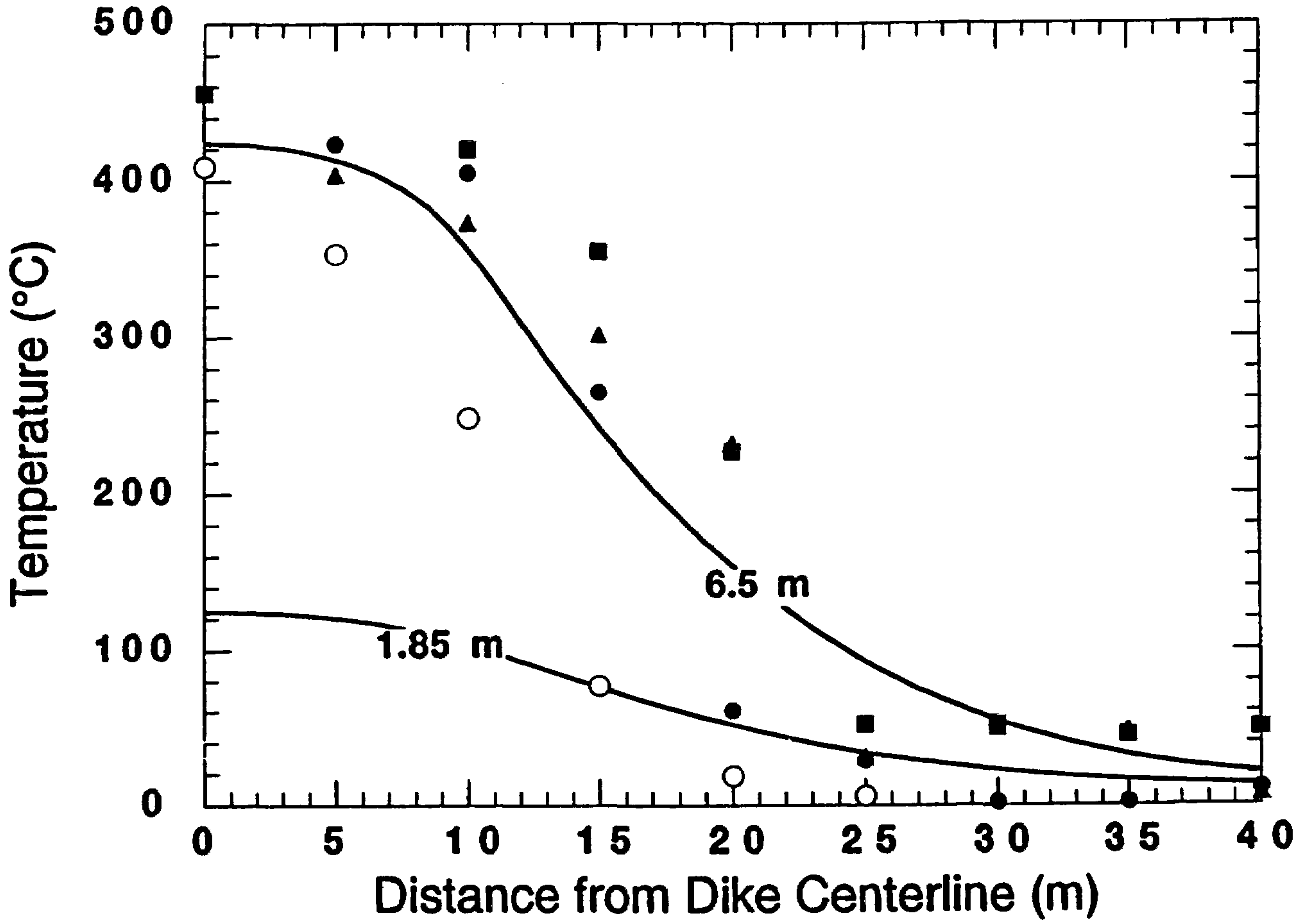


Connor et al. Figure 2

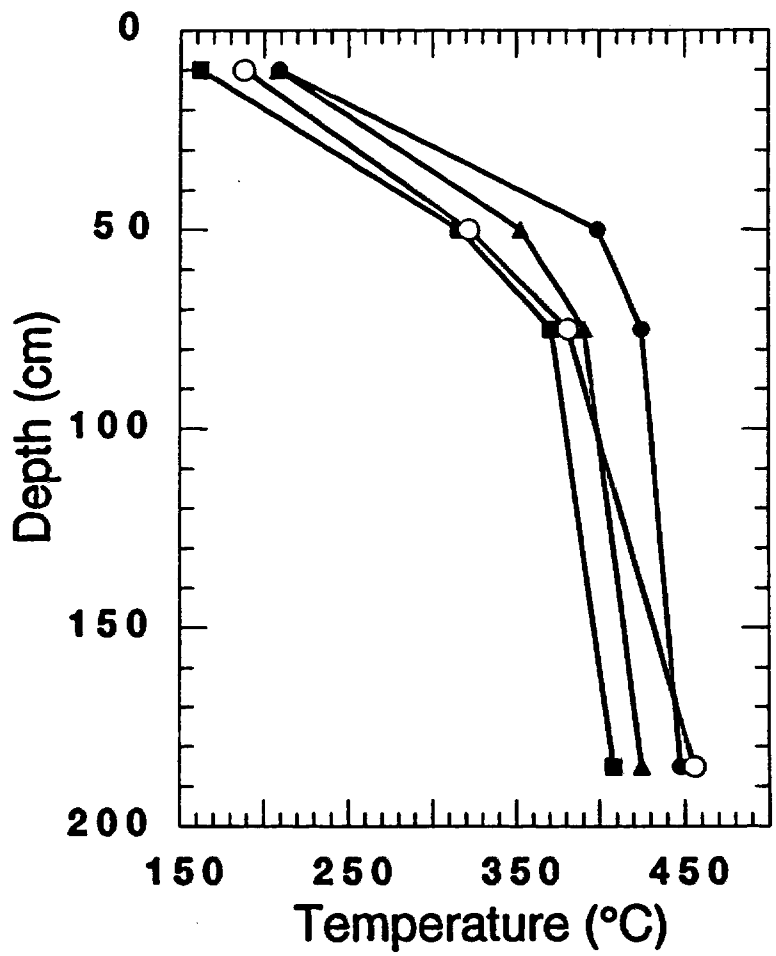
Connor et al. Figure 3



Connor et al., Figure 4



Connor et al., Figure 5



Connor et al. Figure 6