COOLING OF AN IGNEOUS DIKE TWENTY YEARS AFTER INTRUSION

by

C. B. Connor[1], P. C. Lichtner[1], Yu. A. Taran[2], A. A. Ovsyannikov[3], I. Federchenko[3], F. M. Conway[1], B. E. Hill[1], Yu. Doubik[3], V. N. Shapar[3]

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1. Center for Nuclear Waste Regulatory Analyses, Southwest Research Institute, San Antonio, Tx, 78238, USA

2. Intituto de Geofisica, UNAM, 04510, Mexico D.F., Mexico

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

Abstract

The 1975 Tolbachik 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-out 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 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 (GTFE), 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 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).

Three of the cinder cones formed during the GTFE creating a N-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. The ENE-trending valley between the slump block and Cone 1004 is approximately 240 m long and 100 m wide (Figure 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 (Figure 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 hours. 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.

This thermal anomaly 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 SW 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). Twenty-four EM stations were occupied on the Cone 1004 slump block using a large-loop-source. The results indicate a region of very low resistivity exists at depths of approximately 80-300 m beneath the valley that separates the slump block from Cone 1004 (Figure 1). This EM anomaly is interpreted to indicate the position of a volume of rock heated about 600°C. The depth of this low resistivity anomaly correlates well with the elevation of the lava vent (Figure 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 shallow dike that intruded the scoria above this more voluminous intrusion.

Models of Dike Cooling

Surface temperature data alone are not sufficient to uniquely model dike geometry. For instance, 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: (i) a difference in bulk thermal conductivities of the dike and the scoria it intrudes; (ii) heat transfer into the dike from a more voluminous intrusion at depth, as detected by the EM survey; and (iii) 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:

$$\rho C(1-\phi)\frac{\partial T}{\partial t} = \kappa\frac{\partial^2 T}{\partial x^2} ,$$

where T is the rock temperature at time t and distance x within the rock of density ρ, porosity ϕ, specific heat C, and bulk thermal conductivity κ. This equation assumes that heat conduction occurs through the rock matrix and that pore fliuds (e.g., air) are in thermal equilibrium with the rock matrix. The thermal properties of the rock relevant to conductive heat transfer can be summarized as the thermal diffusivity:

$$\alpha = \frac{\kappa}{\rho\, C\,(1-\phi)} .$$

Note that thermal diffusivity is strongly affected by porosity, which affects both bulk density and bulk thermal conductivity (Somerton, 1958; Bailsford and Major, 1964; Beck, 1976). Typical porosity of Cone 1004 scoria is 40-60 percent.

Several equations have been developed to estimate the effect of changing porosity 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 equations. 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, poorly sorted and inflated. Based on the four models (Figure 2), the thermal conductivity of the 1004 scoria is 0.1-0.5 W/m°C. As 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 largely controls thermal diffusivity.

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

Two-dimensional modeling of heat conduction by finite differences (White, 1984) suggests that the top of the dike must be close to the surface of the Cone 1004 slump block, probably within 10 m, even assuming dike widths of up to 10 m. In addition, the high temperatures (> 400°C) observed at a depth of 2 m (Figure 1) can only be achieved if convective heat transfer between the scoria and the atmosphere is inefficient. Otherwise, cooling by convective heat transfer at the surface would have completely cooled the ground above 2 m depth during the last 20 yr. The finite difference models also suggest 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 $\sqrt{\alpha t}$, the rate of heat transfer away from the dike near the surface is not greatly affected by heat transfer from the larger intrusion at depth identified by the EM anomaly.

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, are amply discussed in Tsang and Pruess (1987), Buscheck and Nitao (1993), and Lichtner and Walton (1994). 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 1D suggests that a 5-m-wide dike will be approximately 100°C cooler 20 yr after the dike is emplaced in scoria, if the scoria initially contains an average of 10 percent water and cools by conduction and convection, rather than cooling by pure conduction only (Figure 4). High-temperature gradients near the dike create a dry-out zone within which the volume fraction of water is zero, and heat transfer is by conduction only. In the case of 0.1 initial volume fraction of water, the dry-out zone is 20 m wide after 20 yr of cooling of the 5-m-wide dike, in good agreement with our observations at Tolbachik. Groundwater is vaporizing beyond the dry-out zone. Vaporization of groundwater results in flow of liquid water and water vapor

10/19

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 (Figure 4). 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. Rates of rock alteration are believed to be highest in this zone because of the presence of this two-phase flow at moderate (i.e., 100°C) temperatures. In contrast, rates of rock alteration may be lowest within the dry-out zone closest to the dike, where liquid water is absent. This geometry will persist until the dike cools and the dry-out zone collapses.

Conclusions

Field observations on the Cone 1004 slump block provide empirical evidence that dike cooling can require long periods of time and is significantly impacted by the difference between the thermo-physical properties of the dike and the scoria it intrudes. At Cone 1004, the scoria limits heat flux from the dike, greatly prolonging cooling. Based on rates of cooling over the last 20 yr, this dike will require at least 100 yr to cool below 100°C. Redistribution of moisture in response to the dike intrusion increased saturation 20-40 m from the dike, and completely dries scoria closest to the dike. Development of this dry-out zone limits rates of rock alteration immediately around the dike, but alteration might be more intense at distances of 20-40 m from the dike, in areas of increased water saturation, moderate temperatures, and in the presence of active fluid (water and vapor) flow.

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Table 1. Typical thermo-physical properties for dikes and scoria used in calculations.

	k (dry) (W/m°C)	k (wet) (W/m°C)	Density (kg/m^3)	Specific heat, C (J/kg°C)	Porosity (%)	Permeability (m^2)
Dike	1.7	2.3	2800	840	10	1.0×10^{-14}
Scoria	0.17	0.23	1400	840	50	1.0×10^{-10}

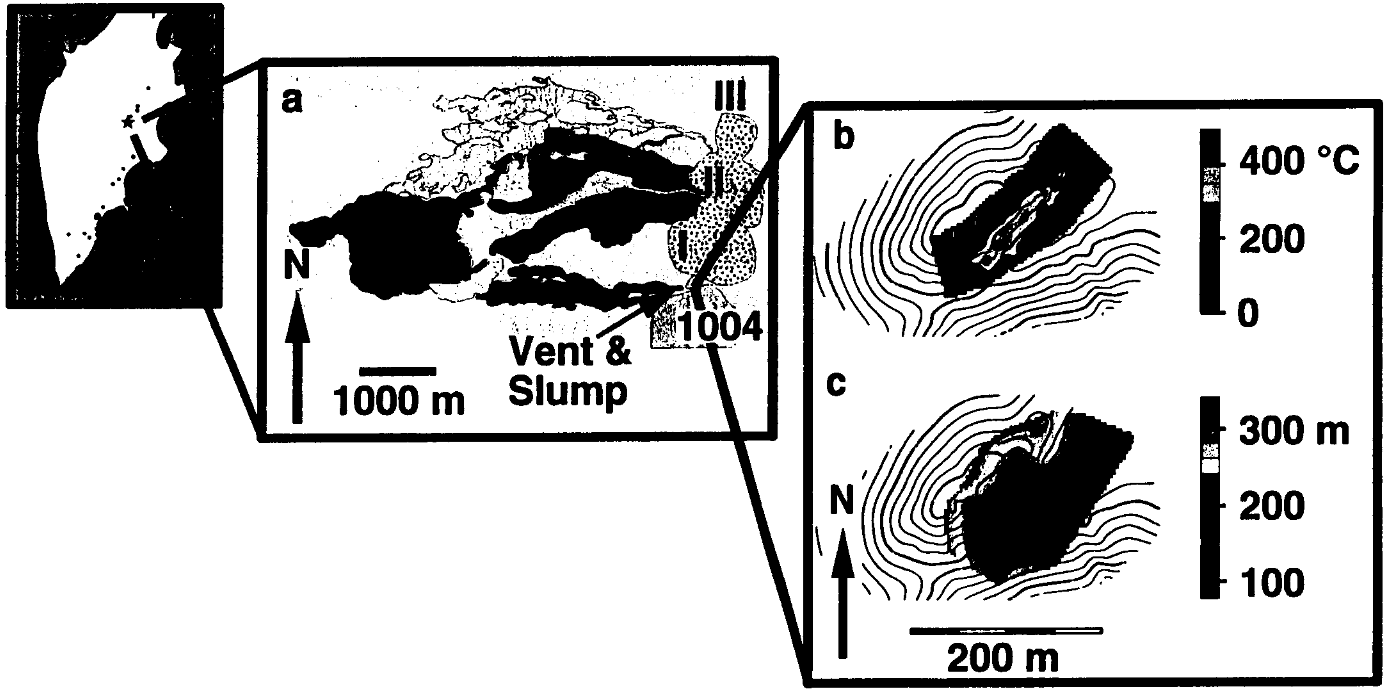
Figure Captions

Figure 1. The Tolbachik cinder cones I-III (modified from Fedotov et al. (1991)) are located on the Kamchatka peninsula . (a) The first lava flow of the eruption (green shading) erupted from a lava vent SW of Cone I, preceded by slumping on the north side of Cone 1004. (b) Anomalous temperatures (>200°C) mapped on the slump block occur within a 30-m-wide, and 160-m-long zone. (c) Twenty-four electromagnetic soundings are interpreted in terms of depth (m) to a 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 a basalt in the 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.

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

Figure 4. Water in the unsaturated zone is redistributed during dike cooling. Twenty years after injection of a 5-m-wide dike into scoria with 10% initial saturation, the dry-out zone extends 15-20 m from the dike contact. A condensation zone develops from 20-60 m , within which saturation nearly doubles and temperature is buffered at approximately 100°C. For these conditions, the dike cools slightly faster than indicated by a pure conduction model with 50% porosity (Figure 3).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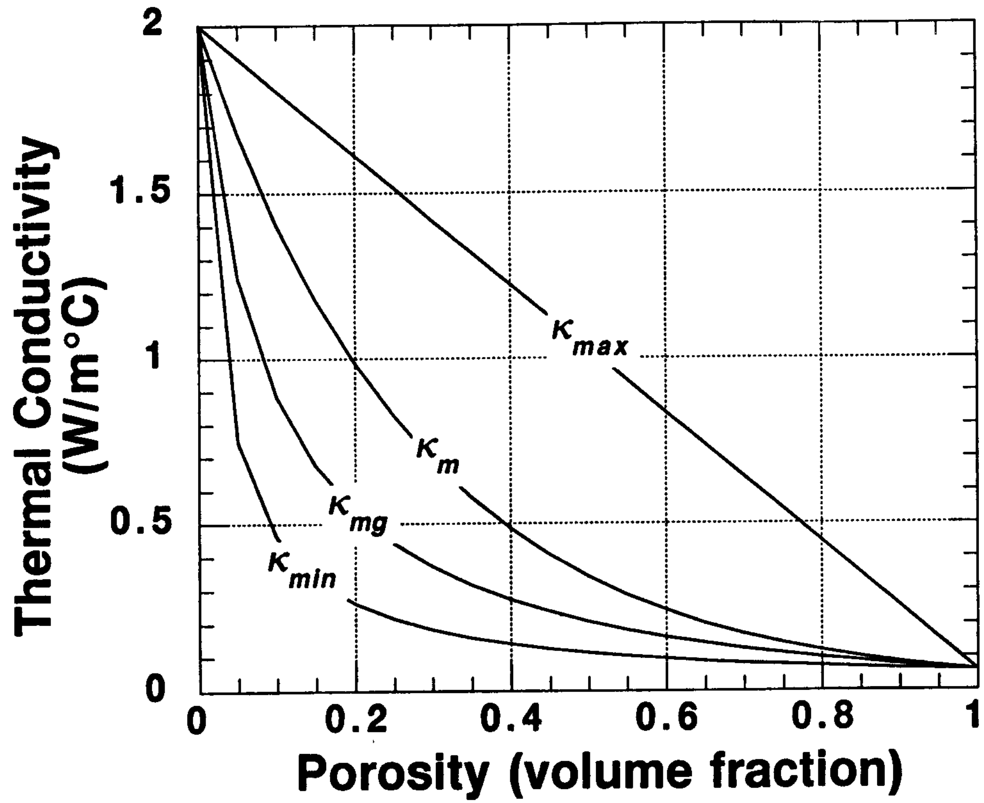
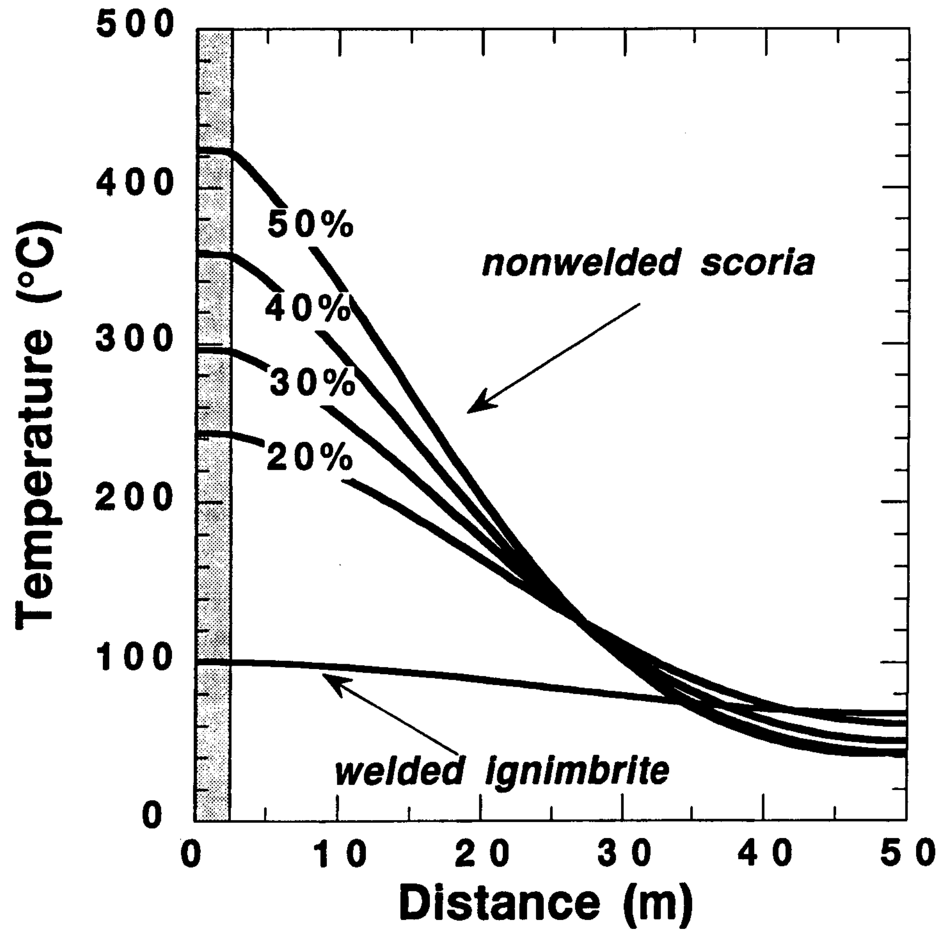


Connor et al. Figure 2

Connor et al. Figure 3



18/15

Connor et al. Figure 4