Three-dimensional model of heat flow in the aureole of the Marcy anorthosite, Adirondack Highlands, New York: Implications for depth of emplacement.

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Abstract

The New Russia gneiss complex occurs within a broad, very high temperature (800-950 °C) metamorphic aureole against the eastern margin of the Marcy anorthosite, northeastern Adirondack Highlands of New York. Three-dimensional models of heat flow from the anorthosite indicate that an aureole like that preserved in the New Russia gneisses would form if the country rock were at high temperature (> 700 °C) and at depth prior to intrusion. These findings are consistent with geobarometric evidence indicating that partial melting in the aureole occurred at 700-1000 MPa and support the hypothesis that the anorthosite intruded at a depth of 25 to 35 km.

Keywords: Marcy anorthosite, Adirondack Highlands, contact metamorphism, conductive heating, finite-difference models.

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Introduction

The Adirondack Highlands of New York expose a Grenville Province outlier that experienced an extended period or periods of granulite-facies metamorphism between approximately 1160 Ma and 1000 Ma. Recent work (Kitchen and Valley, 1995; Alcock and Muller, 1999) has recognized extensive contact metamorphism associated with intrusion of the Marcy anorthosite massif emplaced at ≈ 1130 Ma (McLelland and Chiarenzelli, 1990; McLelland et al., 1996) and presently exposed across ≈ 3000 km^2 of the Highlands. However, the relationship of contact metamorphism in country rock near the Marcy to regional granulite-facies metamorphism and to tectonic and other magmatic events that have affected the region remains in doubt. This results at least in part from distinct models inferring shallow (Valley and O'Neil, 1982; Valley, 1985; Bohlen et al., 1985) and deep (Ollila et al., 1988; Alcock and Muller, 1999) emplacement of anorthosite from seemingly contradictory data. If the Marcy were intruded in the upper crust, then regional moderate to high-pressure metamorphism that affected nearly all rocks exposed in the Highlands, including anorthosite of the Marcy massif, must be a later event (Valley, 1985; Bohlen et al., 1985). Deeper emplacement would obviate the need for distinct low and high-pressure events and would, at least in the northeastern Highlands, allow deformation and metamorphism to be intimately linked to intrusion of anorthosite (Alcock and Muller, 1999). Although deeper intrusion does not require a second metamorphic event, it would not be inconsistent with multiple metamorphic events if other evidence indicates that they occurred.

Proponents of both shallow and deep intrusion have reported similar thermal regimes within the aureole of the Marcy, describing it as having experienced very high temperature metamorphism, with temperatures reaching 900-950 °C in the immediate vicinity of the Marcy and decreasing to ≈ 800 °C or less at about 5 km from the contact (Kitchen and Valley, 1995; Alcock and Muller, 1999). Because thermal conditions within the aureole provide a common ground, the authors of this report initiated a study using three-dimensional finite-difference models of conductive heat flow to determine if the aureole might be used to constrain estimates of emplacement depth.

The Marcy aureole

Kitchen and Valley (1995) report very high temperatures and a gentle thermal gradient away from the Marcy anorthosite (900-800 °C, 0-5 km) based on ^{13}C in cores of graphite grains taken from marbles collected at a number of localities near the massif. (An alternative calibration of the $\Delta^{13}C_{(cal\text{-}gr)}$ thermometer (Chacko et al., 1991) yields temperatures that are approximately 50 °C higher.) Because temperatures estimated from the isotopic signature of graphite cores collected in the immediate vicinity of the Marcy were as much as 100 °C above previous estimates of peak temperature during regional metamorphism, Kitchen and Valley interpret the cores as preserving temperatures obtained during contact heating in the aureole of the anorthosite.

Alcock and Muller (1999) describe the New Russia gneiss complex (Fig. 1) as being part of the contact aureole of the Marcy. The complex occurs within an embayment along eastern edge of the massif and is mostly orthogneiss derived from mangerite, metagabbro, charnockite, and meta-anorthosite. Characteristics of the New Russia gneisses include a penetrative fabric formed during ductile deformation at granulite-facies conditions and the presence of anatectic segregations. Some leucosomes are deformed and appear to have been flattened and aligned with foliation. Others are undeformed and crosscut the foliation of the gneiss.

A similar variety of textures is observed in meta-anorthosite in this area. Layers of meta-anorthosite and gabbroic-meta-anorthosite occur within the New Russia complex and have been deformed with it. However, mildly deformed to undeformed anorthosite of the Marcy massif has been found to crosscut foliation in the New Russia gneiss at 5 localities, and gneissic xenoliths within the anorthosite are common near the massif-New Russia complex contact. This similarity of field relationships implies that penetrative deformation, intrusion of anorthosite and anatexis were approximately synchronous events with intrusion and high-temperature metamorphism outlasting deformation (Alcock and Muller, 1999).

Temperature estimates from ternary feldspar geothermometry (Furman and Lindsley, 1988) range from 900-1000 °C ± 50 within 2 km of the massif anorthosite to 825 °C ± 50 at ≈ 5 km from the massif (Alcock and Muller, 1999; Appendix 1, this paper). Feldspar grains used in the analyses are from undeformed or minimally deformed leucocratic segregations in anatectic mangerite, metagabbro, and charnockite gneiss. Because structural relationships indicate that both anatexis and anorthosite emplacement were syn- to post-tectonic, the temperatures from geothermometry are inferred to reflect heating by the intruding anorthosite.

Temperatures from all but two feldspars fit the regional thermal gradient derived from the Chacko et al. (1991) thermometer. The two exceptions are a ternary alkali feldspar from a sample collected at location 8, near the contact, and an antiperthite from location 3, a contaminated metagabbroic gneiss. Two additional ternary feldspars from location 8 and an alkali feldspar from location 3 yield temperatures that are consistent with the inferred gradient suggesting that the lack of fit for the two outliers may result from special issues. This seems especially likely for the antiperthite measured at location 3 which occurred as a core zone, possibly a relict sub-grain, with a relatively large non-ternary rim. As a result it probably should be excluded from this analysis. It is shown in Figure 2 to maintain constancy with previous reports of feldspar thermometry (Alcock and Muller, 1999). The temperature-distance relationships derived from the ternary feldspar and $\Delta^{13}C_{(cal\text{-}gr)}$ geothermometry support the interpretation that the very high temperature metamorphism near the Marcy anorthosite is a result of contact heating.

Pressure estimates from the aureole

Valley and O'Neil (1982) found very low $\partial^{18}O$ in wollastonite ores near Adirondack anorthosite and attributed the signature to interaction of the ore with meteoric water. From this they inferred emplacement of the anorthosite at depths < 10 km, depths consistent with development of a hydrothermal system driven by heat of the anorthosite (Valley and O'Neil, 1982; Valley, 1985). Kitchen and Valley (1995) accepted this model and, therefore, interpreted high-temperature contact metamorphism to have occurred at low pressure. The aluminum content of pyroxene megacrysts in the anorthosite is also indicative of shallow emplacement (Spear and Markussen, 1997).

Alcock and Muller (1999) use the garnet-producing reactions during dehydration melting of pargasitic hornblende in the New Russia metagabbros to constrain estimates of pressure during anatexis. Experimental fusion of amphibolite, metabasalt, and metagabbro under fluid-absent conditions indicate that garnet stabilizes as a product at pressures in excess of 700 MPa (Wolf and Wyllie, 1993; Rapp and Watson, 1995; Springer and Seck, 1997). Garnet-growth during dehydration melting, therefore, can be used to infer that pressure was greater than 700 MPa during anatexis. Replacement of coronitic textures in the metagabbro by deformation associated with anatexis also suggests relatively high-pressure (Alcock and Muller, 1999) as coronitic textures are estimated to have formed at 700 to 800 MPa (Whitney and McLelland, 1973; Johnson and Essene, 1982). Because anatexis has been correlated with heating by anorthosite intrusion, these pressures would indicate emplacement at depths greater than 20 km.

Intuitively, the very nature of the aureole with its broad extent and very high temperatures seems more consistent with deep than with shallow emplacement. This inference is supported by descriptions of aureoles adjacent to the Laramie and Kiglapait anorthosites. These aureoles, which formed at ≈ 12 and 7-8 km respectively, are marked by steep thermal gradients so that temperature 1 km from the contact is ≤ 500 °C (Russ-Nabalek, 1989; Berg and Docka, 1983). As a test of this inferred correlation between depth of intrusion and breadth of high-temperature aureole, a three-dimensional model of conductive heating by an intrusion similar in shape and size to the Marcy anorthosite was developed to infer possible crustal conditions in which an aureole like the Marcy's might form.

Thermal model

Conductive heat transfer from intrusion to country rock has been modeled with considerable accuracy as one, two and three-dimensional problems (Peacock, 1989; Furlong et al., 1991; references therein). In this experiment, a three-dimensional finite-difference approach has been used to evaluate the effect that emplacement depth of the Marcy anorthosite might have on its aureole. A three-dimensional model with 1.0 km spacing was chosen over computationally simpler one and two-dimensional models so that the shape of the embayment that forms the eastern contact of the Marcy against the New Russia gneiss complex could be included. A two dimensional model combining horizontal and vertical dimensions will not include the lateral transfer of heat from the intrusive promontories that partially enclose the New Russia gneiss and would, therefore, underestimate the peak temperatures achieved during contact metamorphism. Because the object of the experiment was to determine if the breadth and high temperatures of the aureole can be used to constrain estimates of emplacement depth, specifically to determine if intrusion of the Marcy anorthosite at 10 km or less might produce the observed aureole, the experiment was structured to avoid possible underestimates of temperature within the model aureoles. For this reason, three-dimensional models were considered a significant improvement on two-dimensional models that would underestimate of peak temperature within an embayment.

In experimental runs the Marcy was "intruded" as an instantaneous event at 7.5 -12.5, 22.5 - 27.5, or 29.5 to 34.5 km. Space for the intrusion was created by moving country rock down. For example, to model shallow intrusion 5 nodes at 8, 9, 10, 11 and 12 km were assigned magmatic temperature. The geotherm below the intrusion (nodes 13 - 25) was altered then so that each node would have the temperature of a node 5 km higher in the crust before the intrusion (Fig. 3). Multiple-pulse intrusions were also modeled. However, aureoles of multiple intrusions differ from single-pulse intrusions only in the immediate vicinity of the pluton. For his reason, results of those experiments are not reported.

The three-dimensional shape used to approximate the Marcy anorthosite massif in the models (Fig. 4) is based on surface exposure (Isachsen and Fisher, 1970) and an estimated 3 - 4 km current thickness from gravity anomalies (Simmons, 1964) plus an assumed 1 - 2 km removed by erosion. A steeply dipping contact is inferred from the steep gravity gradients that occur across the margins of the Marcy massif (Simmons, 1964) and from field observations (authors' unpublished data). Although a shallowly dipping contact beneath the New Russia complex is unlikely, current data are not conclusive. A one-dimensional model of vertical heat loss from the anorthosite was included in the experiment to determine conditions under which a shallowly dipping contact might produce the thermal gradient measured in the aureole.

The temperature of the intruding anorthosite was set at 1100 or 1200 °C for different experimental runs. The 1100 °C magmatic temperature corresponds to the temperature of the intruding anorthosite estimated from co-existing igneous pyroxenes (Bohlen and Essene, 1978). The 1200 °C runs were made to allow for the possibility that the intruding magma was somewhat hotter. This again represents a conservative approach in an effort to avoid potential underestimates of peak conditions in the aureole.

Initial temperatures of the country rock were set by establishing a two component geothermal equation including a linear term representing mantle heat flux and an exponential term that models heat sources within the crust (Table 1). Normally, the second term represents radiogenic heat production, but it might also be used to reflect temporary heating caused by upper crustal intrusions or volcanic activity that would temporarily concentrate heat in the upper crust. Early experimental runs demonstrated that intrusion of the Marcy into crust with an average geotherm (≈ 20 °C / km) will not produce the high-temperature metamorphism that affected the New Russia gneiss, even if intrusion occurred at depths of 25 or 30 km. Therefore, elevated geotherms were used (Fig. 3). For the shallow-intrusion experiments, geotherms were established that gave temperatures of 554, 675, or 750 °C at a depth of 10 km. Increasing the exponential term produced these very steep thermal gradients in the upper crust. This created a geotherm with constantly increasing temperature with depth without causing totally unreasonable temperatures in the deeper crust.

Model runs with deeper intrusions used elevated geotherms that produced an initial temperature of 750 °C at 25 or 32 km. Geotherms of this type (≈ 30 °C / km and 25 °C / km) are more common geologically than the extreme geotherm used in the shallow-intrusion models because they are likely to form during thermal relaxation of overly thickened crust (England and Richardson, 1977; Peacock, 1989).

Latent heat of crystallization of the magma and heat of reaction in the country rock act as a heat reservoir and sink respectively. Latent heat of crystallization can be estimated using the equations of Burnham and Nekvasil (1986) given the chemical composition of the magma and an average magmatic temperature between intrusion and the solidus. For example, the latent heat of a magma composed of 50% anorthite and 50% albite with an average temperature of 1100 °C can be converted to a release of sensible heat equivalent to a temperature increase of 225 °C. This can be modeled as an increase in the initial magmatic temperature of the intrusion; however, this has the effect of causing an overestimate of temperature in the aureole near the contact (Jaeger, 1964). A better approach is to model a linear release of latent heat over a range of temperatures between intrusion and complete crystallization. This can be accomplished by use of a multiplier that reduces the calculated temperature reduction for each time step over that temperature range (Bowers et al., 1990). The multiplier is chosen so that integrated heat release is to equal the sensible heat equivalent of the latent heat content of the magma. In this experiment the multiplier was set at 0.75 for the temperature range 1100 - 1000 °C for the initial temperature = 1100 °C and 0.5 for the range 1200 - 1000 °C for the initial temperature = 1200 °C. Both multipliers represent a high estimate of latent heat consistent with the conservative approach used in the experiment.

The conservative bias also led the experimenters to discount the heat of reaction during contact metamorphism in the aureole. Zero heat of reaction will allow the greatest heat flux into the broad regional aureole and produces the highest model temperatures in the aureole. This assumption, although clearly understating the effect, may be reasonable for intrusions into already metamorphosed crust. For example, in the New Russia gneiss the dominant reaction involved dehydration melting of amphibole + feldspar without significant transfer of melt from the source rock. Because melting and crystallization occurred at the same location, the net heat of reaction would have been small.

Boundary conditions

Typically, boundary conditions are established in finite-difference models by placing the vertical and the lower horizontal boundaries far from the intrusion so that temperatures at the boundary remain fixed. However, because the experiments were run using a G3 Macintosh computer with code written in Visual Basic of Microsoft Excel, very large arrays (> 45, 35, 50) led to software errors that prevented execution of the program. As a result placing the boundaries at far distances was not possible. Instead boundary conditions, other than the upper surface which was held constant at 0 °C, were set by assuming that temperature change at the edges of the model was linear. This allows one to use ΔT at the 2 closest interior nodes to predict ΔT at the edge node (see Table 1 for algorithm). The ability of these boundary conditions to produce results consistent with more standard models was tested in a two dimensional experiment. Thermal gradients adjacent to an intrusion were modeled using the algorithm given in Table 1 and with boundaries placed far from the intrusion. Temperature differences resulting from the two approaches were less than 0.1 °C at the node nearest the intrusion. It is thought that the algorithm presented here should be valid so long as the distance to a thermal anomaly outside the model is no closer to the boundary than the contact of the intrusion within the model.

It should be noted that a model is only as good as its ability to accurately mimic the physics of the intruding, crystallizing magma, and reactions in the country rock. Results of the experiment should, therefore, be viewed as an approximation of a very complex problem.

Discussion

Several variables control the extent of the high temperature aureole that forms adjacent to large intrusions. Most important are the ambient temperature of the country rock at the time of emplacement, the temperature of the magma, depth of emplacement, latent heats of crystallization and reaction, and the shape of the intrusion.

Temperature of the country rock (T_{NR}) is the most significant variable determining peak temperatures within the aureole. Geothermometry indicates that temperatures in the aureole (T_{aur}) preserved in the New Russia gneiss exceeded 800 °C at a distance of 5 km from the Marcy anorthosite. Only those experimental runs with $T_{NR} \geq 700$ °C produced aureole temperatures > 800 °C at 5 km. Also important is the initial temperature of the intruding magma (T_m). If the T_m was 1100 °C, then the minimum T_{NR} to produce a temperature of 800 °C at 5 km would be 750 °C. Composition of the magma and pyroxene-thermometry (Bohlen and Essene, 1978), indicate that experimental runs at 1100 °C are more likely to correspond to the physical reality of the intruding anorthosite. However, as discussed above extreme conditions were modeled in the experiments to avoid underestimating temperatures in the aureole.

Depth of emplacement impacts the thermal gradient within the aureole in two ways. First, the T_{NR} is controlled by depth of emplacement and the local geotherm. Second, because the rate of heat loss to the surface is negatively correlated with depth, deeper emplacement will result in greater lateral heat flux and higher temperatures in the lateral aureole (Jaeger, 1964).

The first effect can be demonstrated considering a range of "average" geotherms. For example, near surface geotherms typically are between 10 and 50 °C/km; and an intrusion emplaced at 10 km might, therefore, contact rock with initial temperature between 100 and 500 °C. Under these conditions, the contact aureole would produce a steep thermal gradient. Even if T_{NR} were 550 °C, T_{aur} at 5 km are ≈ 600 °C (Fig. 6). The steep lateral gradients with very high temperatures limited to country rock within a few hundred meters of the contact are similar to the observed aureoles adjacent to the shallowly intruded Kiglapait and Laramie anorthosites (Berg and Docka, 1983; Russ-Nabalek, 1989). Average geotherms to the deeper crust will be more moderate than those found near the surface, generally between 15 and 30 °C/km. Therefore, crustal temperature at depths ≥ 25 km may reach 750 °C, especially in terranes undergoing thermal relaxation after orogenesis (England and Richardson, 1977 among others). Experiments run with model T_{NR} = 750 °C at 25 and 32 km both produced T_{aur} ≈ 800 °C at 5 km from the contact (T_m = 1100 °C).

Although there is not evidence for an exceptional regional geotherm prior to metamorphism in the Grenville province of Canada and the Adirondacks, examples of exceptional thermal gradients have been reported elsewhere. For example, a 75 °C/km gradient has been inferred from low-pressure granulite-facies metamorphism in the Mt. Stafford area, Australia (Vernon et al., 1990). Because such exceptional geotherms exist, shallow emplacement was also modeled with geotherms producing temperatures of 675 and 750 °C at a depth of 10 km. Only those intrusions modeled as entering 750 °C crust produced thermal gradients within error of observed metamorphic temperatures; however, several considerations indicate that the result should not be taken as evidence that the aureole observed near the Marcy may have formed at low pressure. First, the thermal gradient preserved in Mount Stafford area is a regional geotherm perturbed by contact metamorphism (Vernon et al., 1990). Second, calc-silicate assemblages such as phlogopite-calcite-quartz, tremolite-calcite and tremolite-calcite-quartz (Valley and Essene, 1980) which can be stable at inferred regional metamorphic conditions (T 700 - 750 °C, P ≈ 750 MPa) would not be stable at 750 °C, 300 MPa. Because these assemblages are relatively common in marbles of the Highlands and because they are described as prograde assemblages (Valley and Essene, 1980), it seems unlikely that the region experienced a regional geotherm approaching 75 °C/ km at the time of anorthosite intrusion. Third, experimental conditions were consistently conservative for the purposes of this study, overestimating heat of crystallization and underestimating heat of reaction in the aureole. As a result the estimate of 780 °C at 5 km from the contact represents a maximum T_{aur} for that distance. Fourth, the geotherms were modeled as steady state geotherms prior to intrusion. The model, therefore, implies that the elevated geotherm at 10 km is produced by an unreasonable concentration of radiogenic elements in the upper crust. If a non-steady state geotherm such as one produced by magmatic activity in the upper crust were used and a more reasonable radiogenic heat production included, for example, 2 x 10^{-6} W/m^3 (Peacock, 1989), then the crust at 10 km might cool at ≈ 75 °C/ Ma (from one dimensional model). This implies that the models may overestimate aureole temperatures in the shallow crust by 30 to 50 °C since greatest heating occurs in the first 0.5 Ma.

As noted, depth of emplacement also affects the aureole because heat loss from the intrusion is greatest in the vertical direction toward the surface. The effect is more important near the surface and increases in importance as the geothermal gradient increases. The result is a narrowing of the lateral aureole at shallow depths so that at a depth of 10 km, heating at a distance of 5 km (horizontal distance) from the contact is less than would occur at a depth of 25 or 32 km (Fig. 5). With other model conditions held the constant, aureoles at 25 and 32 km produced temperatures ≈ 25 °C higher than the model at 10 km.

The position of the aureole relative to embayments and promontories in the intrusion is also important (Fig. 6). The majority of New Russia complex lies within an embayment which had the effect of broadening the aureole. However, the importance of this effect is secondary to the initial temperature of the country rock and is not sufficient to produce a broad, high-temperature aureole at shallow crustal level except under exceptional conditional.

A possible source of error in the models is a difference between estimated and true shape of the anorthosite in the subsurface. The thermal gradient within the aureole is measured against horizontal distance and it is possible that the anorthosite extends to the east of the exposed massif with a shallowly dipping contact against the New Russia gneiss. As stated previously, neither geophysical evidence nor field observations support this possibility. Even should the anorthosite occur only a few hundred meters below the current erosion surface, the high temperatures of the aureole require very high temperatures in the country rock prior to intrusion. This can be demonstrated by a one-dimensional model for vertical heat loss above an 1100 or 1200 °C intrusion into crust with elevated geotherms ≈ 45 or 70 °C / km (Fig. 7). Node spacing was set at 25 m to allow for better definition of the gradient near the anorthosite. Results indicate that very high temperatures are limited to distances of 100 - 200 m of the anorthosite except when the initial T_{NR} and T_m are both very high. In fact, the anorthosite must be so close to the surface that it should crop out at lower elevations across the region because topographic relief is 250 - 300 m. Alternatively, such a strong vertical gradient is produced that one should find significantly lower grade rock at higher elevations. Neither condition is met. Even should initial conditions have been such that T_{NR} = 600 °C at a depth of 8 km, the dip of the contact must be 5 degrees or less to produce temperatures > 800 °C in the aureole at the current horizontal distance of 5 km. Such a shallow dip would cause the contact of the Marcy to be strongly controlled by topography, which runs counter to our experience in the field. Given these experimental results and the evidence that supports a relatively steep contact, it seems unlikely that the aureole of the Marcy preserved in the New Russia gneiss complex results from the presence of large volumes of anorthosite just below the present erosion surface.

Another assumption that might be question is the use of a non-convecting magma in the models. Convection in the magma chamber would have the effect of equalizing temperature across the chamber, raising the temperature of the magma near the intrusive contact. This might raise temperature in the aureole. To test the effect of convection, a two-dimensional model of a rectangular intrusion was constructed. Temperature of the magma was averaged after each time step. If average T_m remained above 1050 °C, nodes within the chamber were reassigned the average temperature. The effect of convection was to increase temperature of the aureole at the corners of the intrusion and reduce temperature in the middle of a side. Applying this result to the Marcy anorthosite indicates that convection would transfer heat from the embayment to promontories, reducing aureole temperatures in the New Russia complex.

One might also be concerned that temperatures interpreted to result from contact heating are, in fact, evidence of high temperature during regional metamorphism. For example, if the peak temperature 825 °C at 5km from the contact results from regional metamorphism, then we cannot reconstruct the true gradient within the aureole. This is why the observed structural and textural relationships among anatectic segregations, gneissic fabric, and the intrusive contact of the massif anorthosite are so important. It is these relationships that allow us to establish that temperature estimates from different samples are derived from the same event and that that event is directly related to emplacement of the anorthosite.

Experimental results, therefore, demonstrate a strong correlation between shape, breadth and peak temperature of the aureole with depth of emplacement both because deeper sections of the crust are hotter and because heat loss to the surface will be more rapid in the upper crust. Results of the thermal model imply that the Marcy anorthosite was intruded into an already hot crust, $T \approx 750$ °C. Although shallow emplacement of the Marcy cannot be ruled out, they do indicate the extreme difficulty of reconciling the broad, high-temperature aureole of the massif with inferred emplacement at 10 km or less. Formation of the aureole at shallow levels could only occur if the geothermal gradient in region were ≥ 75 °C / km (250 - 300 °C/100MPa) prior to intrusion. If shallow emplacement did occur, then the experimental results reported here indicate that the Adirondack Highlands experienced regional low-pressure granulite-facies metamorphism. Regional temperatures of 750 °C are much more likely to be reached at depths of 25 km or more. The experimental results, therefore, are more consistent with emplacement of the Marcy anorthosite at depth and support estimates of emplacement at 25 to 35 km inferred from anatectic reactions in the Marcy's aureole.

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Table 1: Summary of Experimental Conditions, Constants and Methods

Temperature of Intrusion	1100 ˚C		1200 ˚C
Depth of Intrusion	7.5-12.5 km	22.5-27.5 km	30.5-35.5km
Latent Heat of Crystallization			
1100 ˚C magma (1100-1000 ˚C)		$0.75 \bullet \Delta T$	
1200 ˚C magma (1200-1000 ˚C)		$0.5 \bullet \Delta T$	
Heat of Reaction		0.0	
Thermal Diffusivity (κ)		$8.3 \bullet 10^{-7}\ m^2/s$	

Model Equation to Establish Geotherm

$$T_{i,j,k} = 0 + \frac{q_m z}{k} + \frac{AL}{k}(1 - e^{-z/L})$$

(After Peacock (1989). q_m is mantle heat flux (W/m^2); z is depth (m); A is heat production in the crust (W/m^3); L is characteristic length (m); and k is thermal conductivity (W/m-K).

Boundary Conditions

Upper Surface: T = 0°C

Other Surfaces (Sample Algorithm):

$$x = T^{n+1}_{i,2,k} - T^{n}_{i,2,k}$$

$$y = T^{n+1}_{i,3,k} - T^{n}_{i,3,k}$$

$$w = x - y$$

$$T^{n+1}_{i,1,k} = T^{n}_{i,1,k} + x + w$$

Finite Difference Equation

$$T^{n+1}_{i,j,k} = T^{n}_{i,j,k} + (\kappa \bullet t(T^{n}_{i,j,k-1} - 2T^{n}_{i,j,k} + T^{n}_{i,j,k+1})/z^2$$
$$+(\kappa \bullet t(T^{n}_{i,j-1,k} - 2T^{n}_{i,j,k} + T^{n}_{i,j+1,k})/z^2$$
$$+(\kappa \bullet t(T^{n}_{i-1,j,k} - 2T^{n}_{i,j,k} + T^{n}_{i+1,j,k})/z^2$$
$$+B \bullet e^{z/L}$$

($T^{n+1}_{i,j,k}$ is new temperature at node i,j,k; t is time (s); and B is a constant for heat production in the crust (Kelvins).)

Appendix 1: Feldspar Thermometry[1]

Samp.				Comp. of Lamellae				Integrated Composition				
Map #	Modal %		n	Ab	Or	An	n	Ab	Or	An	Dist. [2]	T
190	Pl-1	12.7	10	74.0	0.6	25.4	2				0.3	850
8	Pl-2[3]	26.2		35.8	62.6	1.6		24.3	72.0	3.8		
	Or	61.1		8.9	90.9	0.2	4					
190a	Pl-1	13.8	3	75.3	0.7	24.0	3					
8	Pl-2	56.0		62.3	35.2	2.5		48.7	46.5	4.8		900
	Or	30.2		11.3	88.5	0.3	4					
190a	Pl	76.5	5	62.3	1.0	26.6	3	58.6	20.8	20.5		970
8	Or	23.5		13.8	85.7	0.5	3					
155	Pl-1	16.4	9	80.5	0.6	18.9	3				5.2	
9	Pl-2[3]	29.1		44.9	53.7	1.4		31.1	65.3	3.6		830
	Or	54.6		8.9	90.8	0.3	3					
11A[4]	Pl	61.9	5	84.5	1.0	14.5	8	56.2	34.8	9.1	2.0	925
10	Or	38.1		10.1	89.8	0.1	9					
11A	Pl	62.3	3					56.4	34.5	9.1		925
10	Or	37.7										
11A	Pl	67.1	3					60.0	30.2	9.8		925
10	Or	32.9										
217	Pl	26.7	5	85.3	0.7	14.0	4	30.0	66.1	3.9	5.5	850
11	Or	73.3		9.9	90.0	0.1	6					
217	Pl	26.2	8					29.7	66.6	3.8		850
11	Or	73.8										

Notes: 1. Additional feldspar analyses obtained after submission of Alcock and Muller (1999).

2. Distance is approximate distance in km from sample location to nearest outcrop of massif anorthosite.

3. Mesoperthites from 190 and 155 contain two distinct populations of plagioclase lamellae. Albitic lamellae are thin and could not be resolved for point analysis. Lamellae compositions were determined by subtracting orthoclase host material from broad-beam, area analyses.

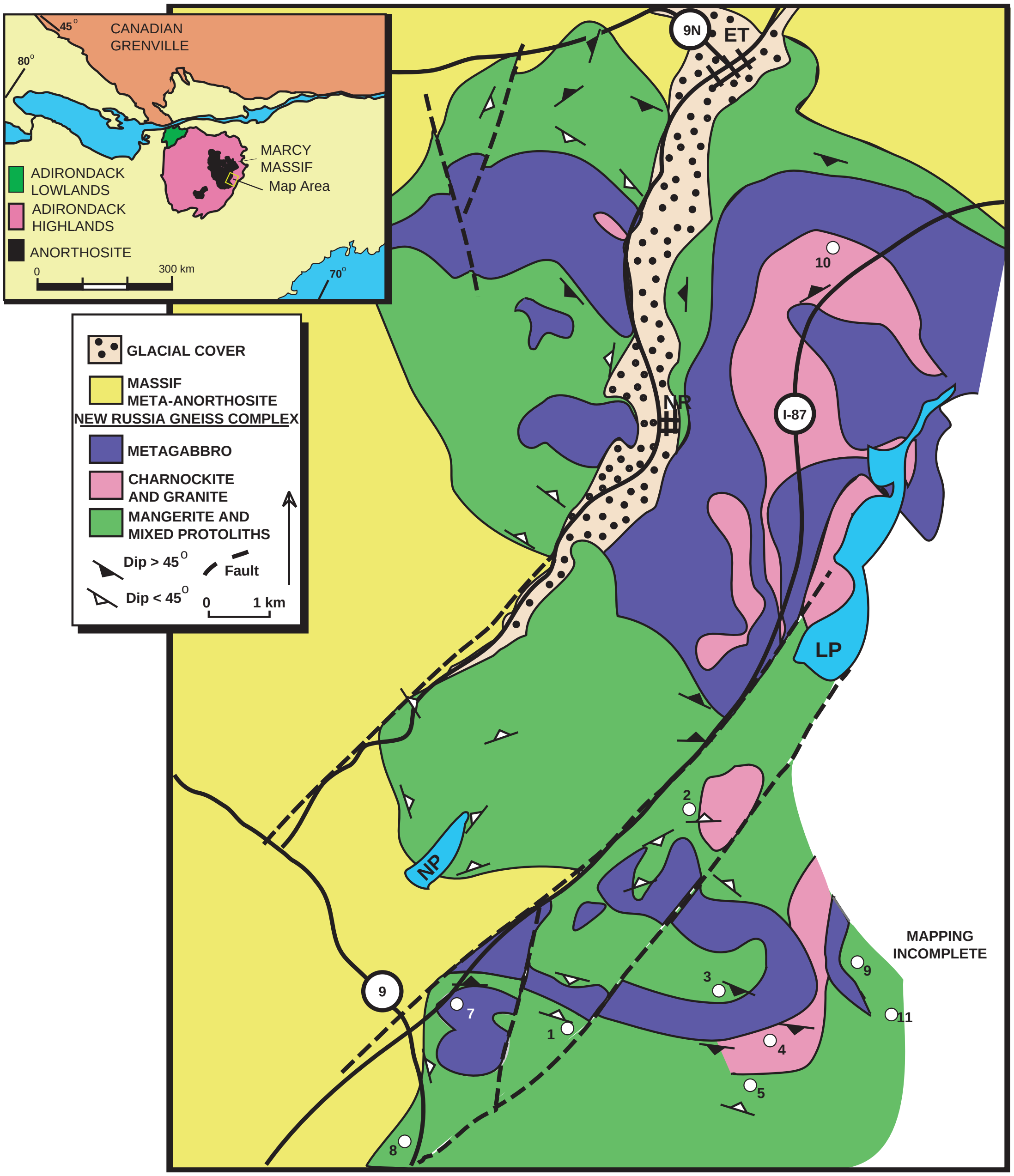

Figure 1. Surficial geology of the Elizabethtown region, NE Adirondack Highlands, NY. Locations of samples used for geothermometry are identified by number. Sample 6 is not from map area. It was collected approximately 1.5 miles south of Moriah on Essex Co. Rte. 7. ET is Elizabethtown; NR, New Russia; LP, Lincoln Pond; and NP, New Pond.

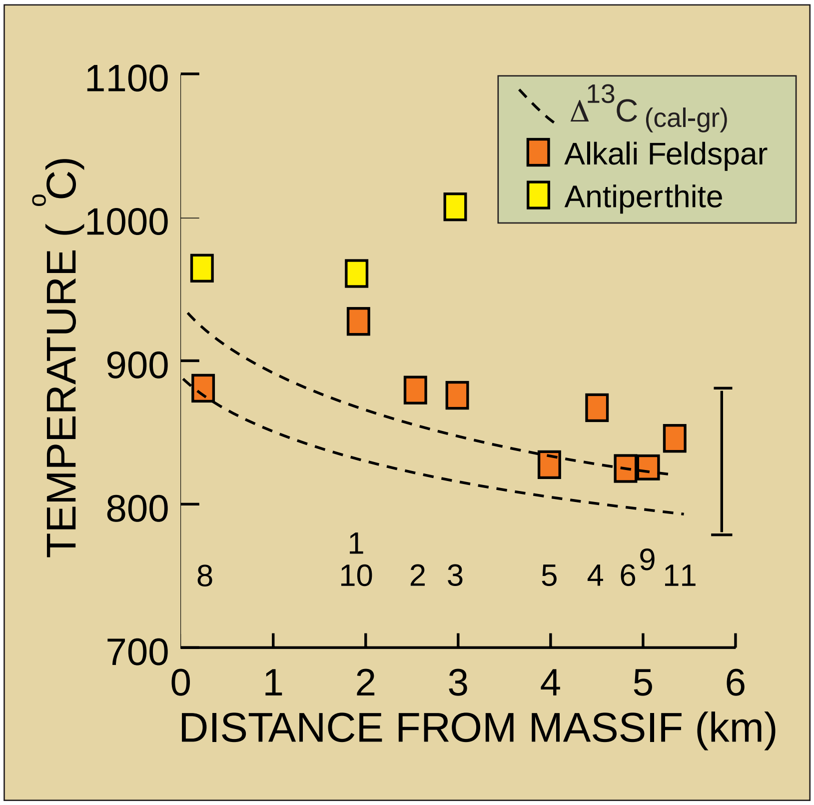

Figure 2. Results of ternary feldspar geothermometry plotted against distance from Marcy anorthosite massif. If multiple grains from a single sample were analyzed, temperature plotted is an average temperature. Also shown are thermal gradients inferred from $\Delta^{13}C_{(cal-gr)}$. Lower curve uses temperatures from Kitchen and Valley (1995). Upper curve uses thermometer of Chacko et al. (1991). Standard error bar of ± 50 ˚C is included for reference.

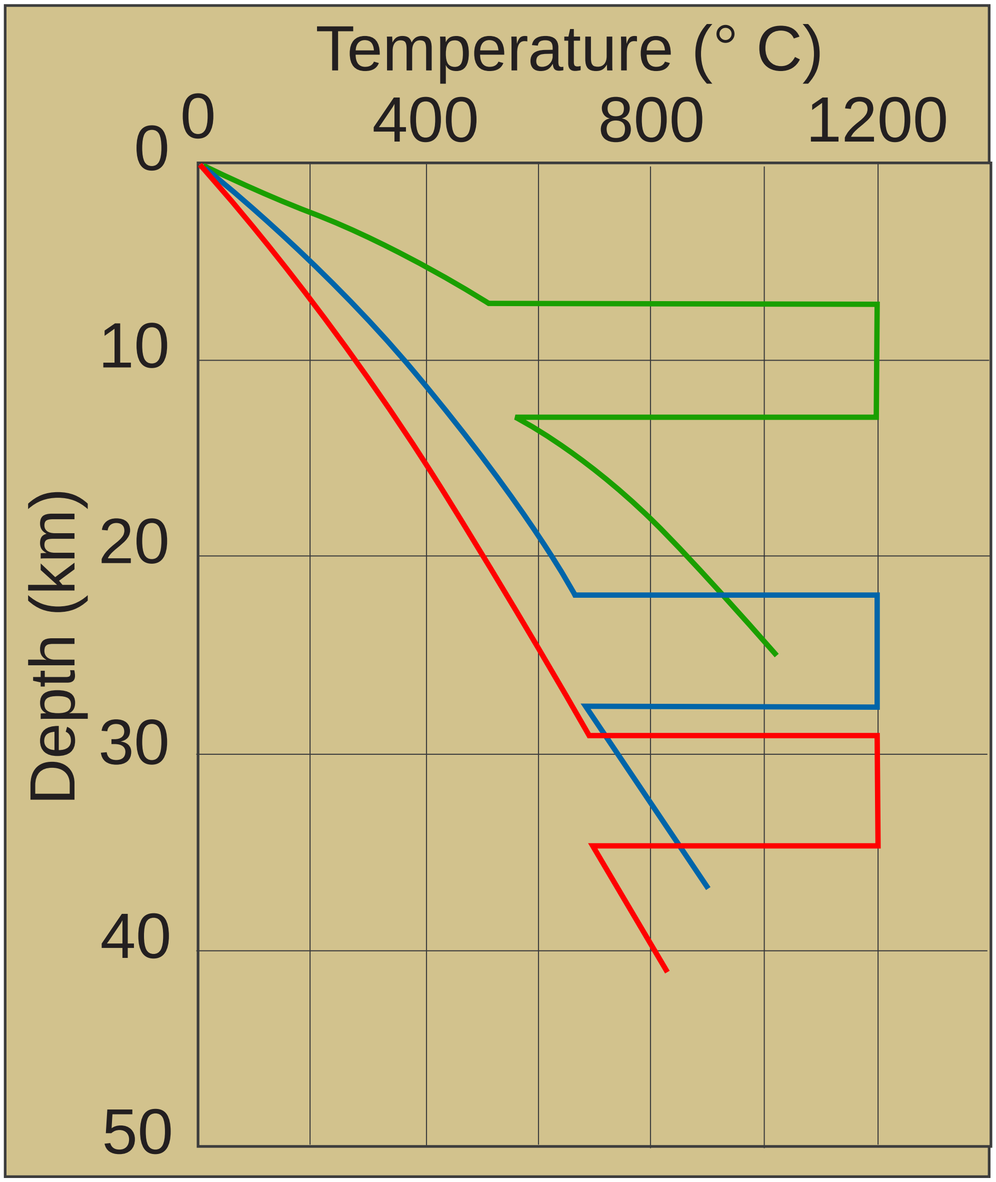

Figure 3. Initial conditions after intrusion for models with T_{NR} = 675 ˚C at 10 and T_{NR} = 750 ˚C at 25 and 32 km.

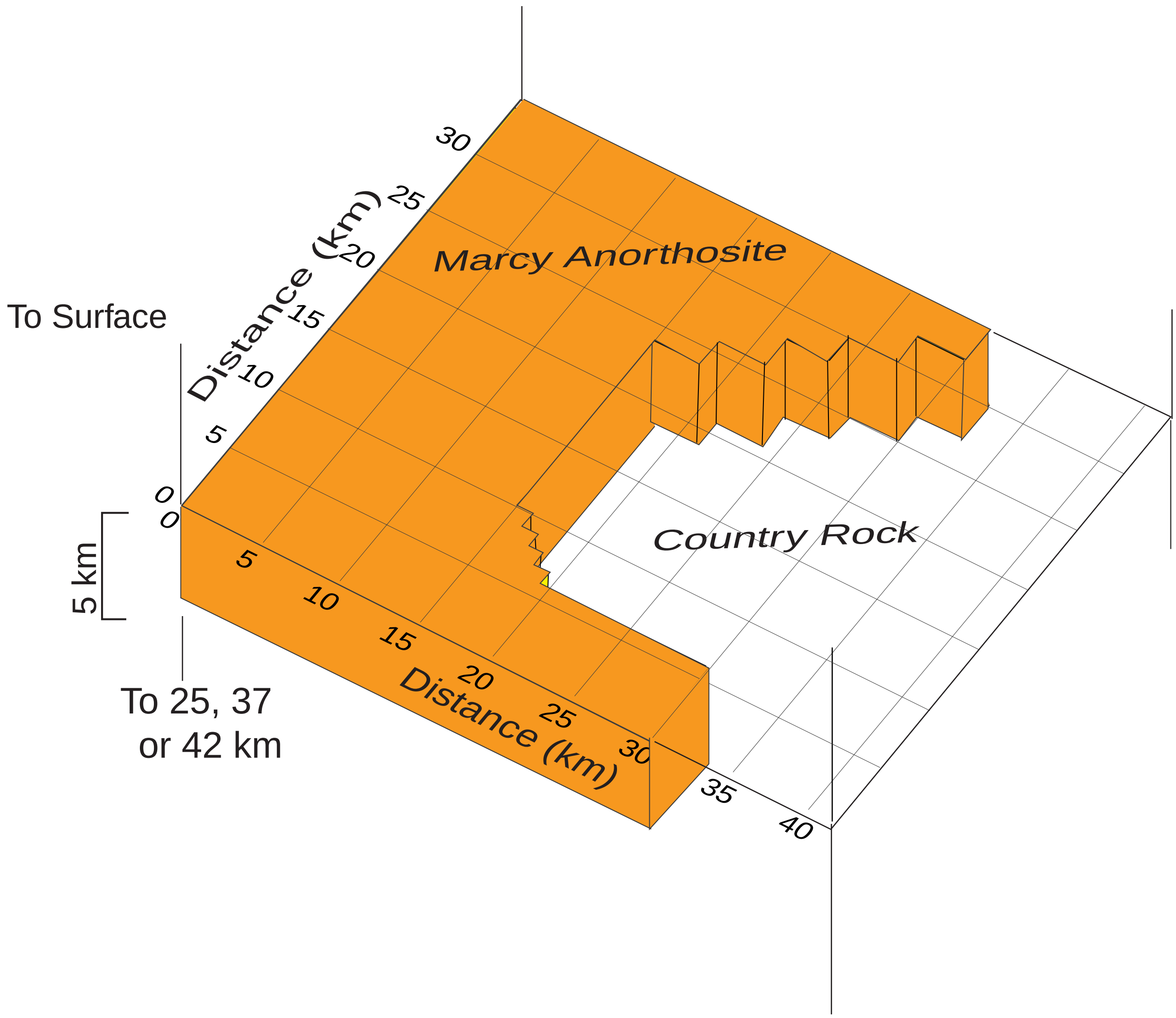

Figure 4. Shape of intrusion used in finite difference model. Model boundaries of the intrusion are closer to the contact included in the model than to any contact external to the model as shown on the Adirondack Sheet of the geologic map of New York (Isachsen and Fisher, 1970). Upper boundary is the earth surface. Lower boundaries are 25, 37 and 42 km for shallow, intermediate and deep intrusions, respectively.

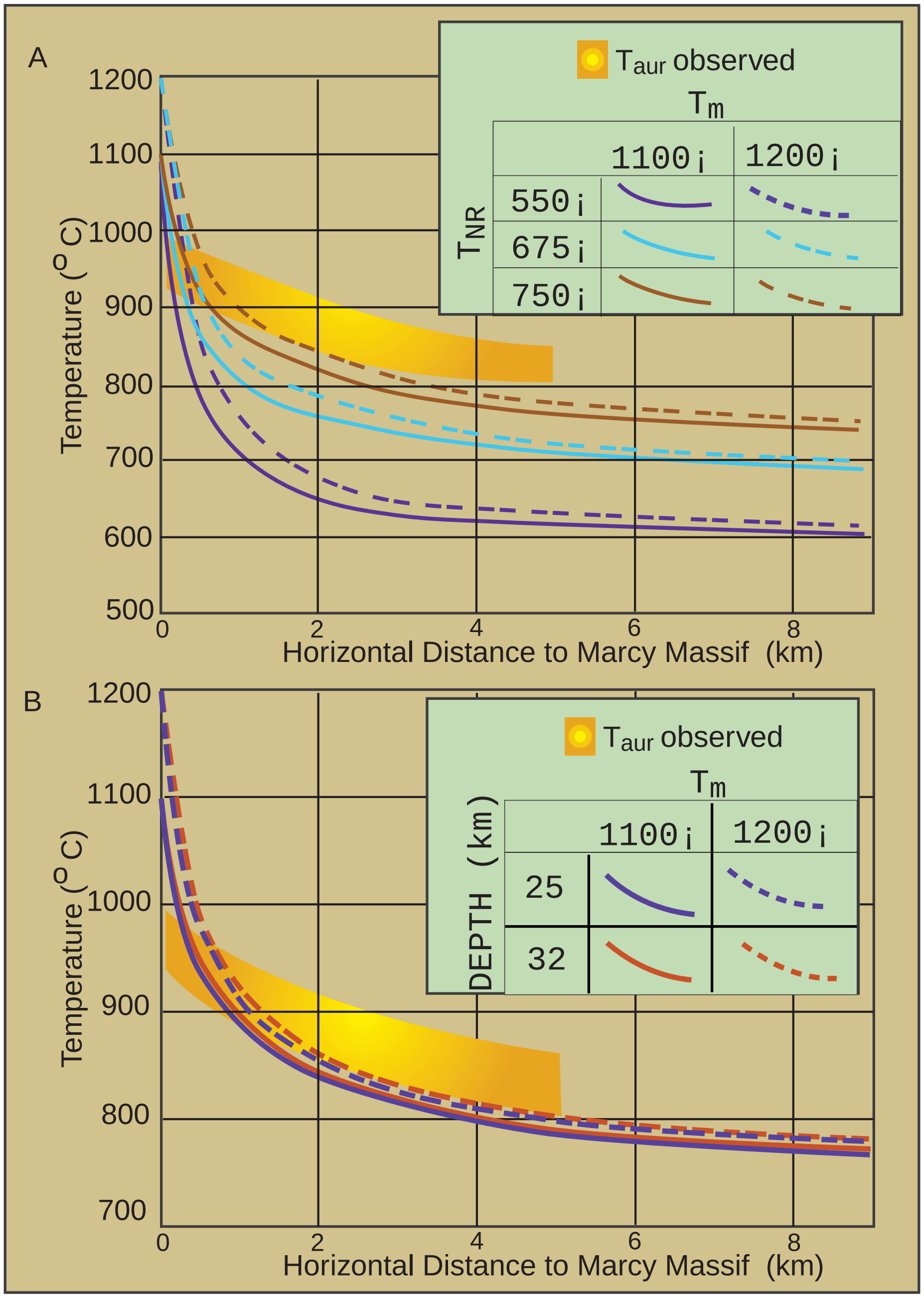

Figure 5. Thermal gradients from finite difference models shown as linear plots analogous to Figure 2. (a) Results for shallow emplacement. Note that no model results overlap geothermometric estimates of T_{aur} at distances greater than 3 km from the contact and that the most geologically reasonable initial condition (T_{NR} = 550 ˚C, T_m = 1100 ˚C) overlaps observed aureole only at distances less than 0.5 km from the contact. (b) Results from experiments run at depths of 25 and 32 km. Temperatures plotted are peak temperatures reached at a particular node during conductive heating.

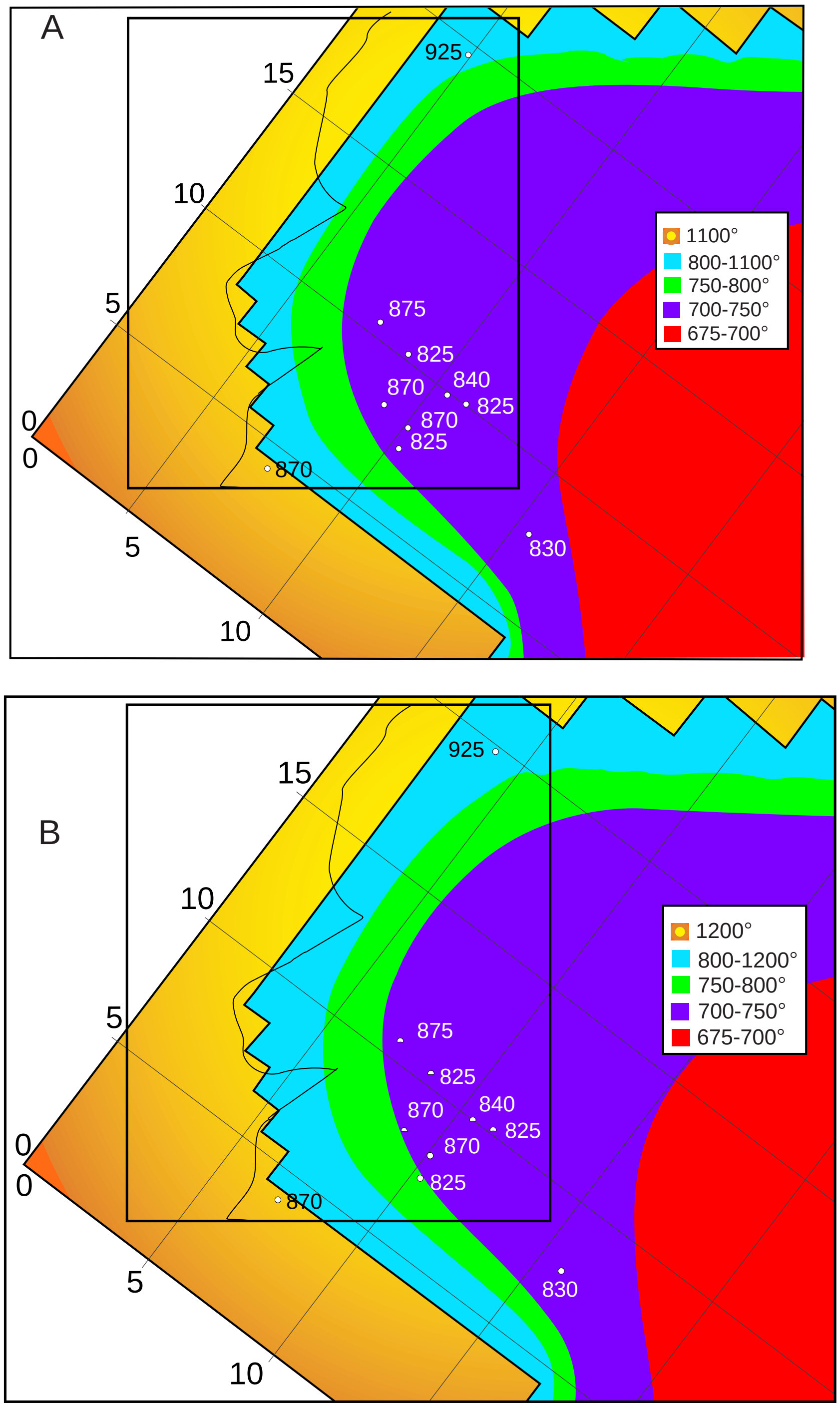

Figure 6. Contoured results of finite difference models at depths of 10 km (a and b), at 25 km (c), and at 32 km (d) with T_{NR} = 675, 675, 750, and 750 ˚C. Temperatures contoured are the highest temperature reached at each node during conductive heating by the intrusion. The surface shown is implied to be current erosion surface. Overlay shows map area of Figure 1 with sample locations and results of feldspar thermometry. Irregular but approximately N-S line within inset is mapped contact between massif anorthosite and New Russia gneiss complex.

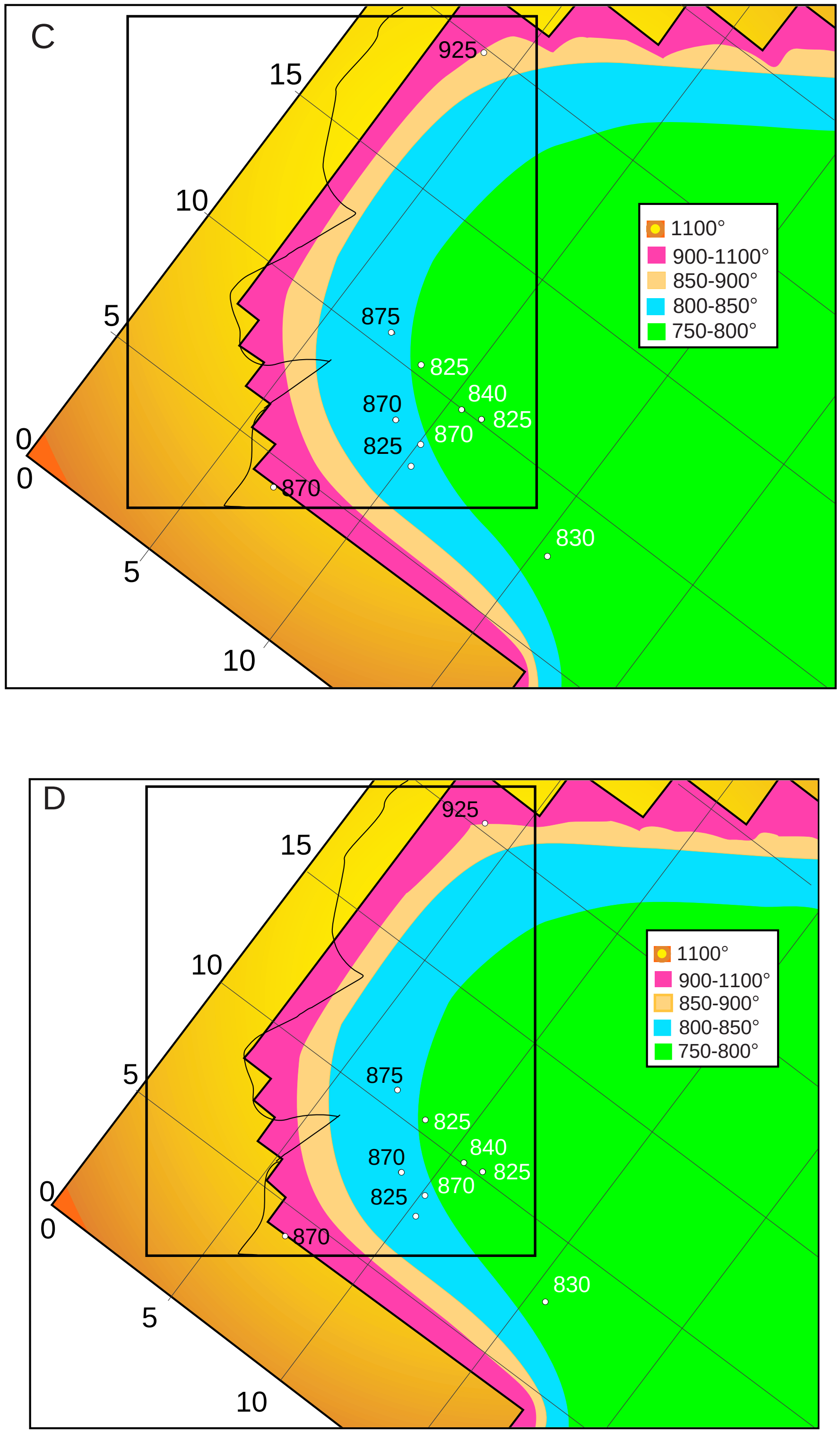

Figure 6. Continued.

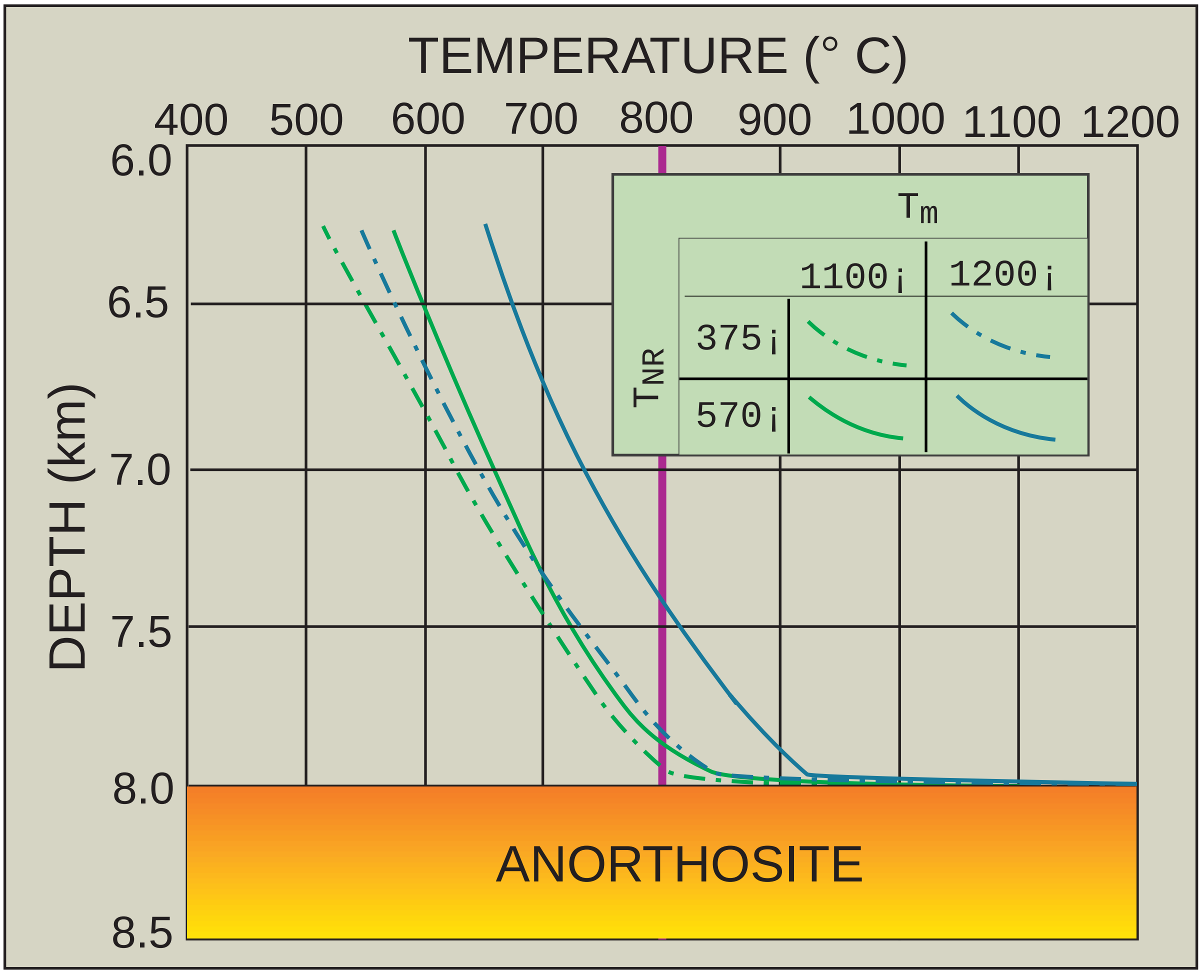

Figure 7. Results of one-dimensional finite difference models for vertical heat loss above an intrusion emplaced at 8 to 13 km. Note that only high magmatic temperature (T_m = 1200 ˚C) and high regional geotherm (> 70 °C / km) produce aureole temperatures > 800 °C more than 200 m from the contact. Temperatures plotted are peak temperatures reached at a particular node during conductive heating.