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Henry J. Ramey, Jr., Roland N. Horne,
Paul Kruger, Frank G. Miller,
William E. Brigham, Jean W. Cook
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Modelling of Terrain-Induced Advective Flow in Tibet: Implications for Assessment of Crustal Heat Flow

M.P. HOCHSTEIN and YANG ZHONGKE

Geothermal Institute and Department of Engineering Science,
University of Auckland, NZ

Abstract

In steep terrain the effect of advective flow can be significant, as it can distort the temperature field in the upper brittle crust. The effect was studied by modelling advective flow across a large valley system in Tibet which is associated with several geothermal hot spring systems, the Yanbajing Valley. It was found that, in this setting, all near-surface temperature gradients are significantly disturbed, attaining values differing by up to half an order of magnitude from those resulting from conductive heat transfer. Allowing for advective effects, it was found that the crustal heat flux within the Himalayan Geothermal Belt lies within the range of 60 to 90 mW/m^2 in the Lhasa-Yanbajing area.

Introduction

Over 1000 hot and warm springs occur in Tibet. They are manifestations of numerous low and high temperature systems associated with deep-reaching fracture zones. High temperature systems (as indicated by cation geothermometers) discharging significant heat (say, >3 MW) at the surface are rare. Using the inventory of Zhang Zhifei and Zhang Mingtao (1985) and our own field observations, it was found that heat losses of some Tibetan systems have been over-estimated (Hochstein, 1988). There are probably only 5 high temperature systems with a natural heat discharge in the range of 30 to 100 MW; the majority of high temperature systems are associated with moderate discharges of the order of 3 to 30 MW. If one plots on a map (see Fig. 1) all prospects that discharge fluids close to boiling point temperatures, they fall within a 150 to 200 km wide belt which, in the framework of Plate Tectonics, lies in front of the indenting Indian Plate. Chinese scientists have called this belt the 'Himalayan Geothermal Belt (HGB)' (Tong W. and Zhang M., 1981).

It has been inferred that the HGB is associated with an anomalously hot upper crust; a high terrestrial heat flux has been postulated to explain the geothermal activity and the anomalous crustal temperature field (Wei S. and Deng X., 1989). Heat flow measurements by Francheteau et al. (1984) in two shallow lakes on a plateau south of the Yarlung Zangpo River (Puma Lake and Yamtso Lake in Fig. 2) provided some evidence for the postulated high crustal heat flow (observed values lie between 90 and 147 mW/m^2).

Efforts to trace the lateral extent of the inferred anomalous heat flow across the belt by measurements in drillholes have been less successful. Most deeper wells in Tibet have been drilled into geothermal reservoirs or associated outflow structures. Data from a few wells in the Lhasa area (Shen, 1989), far away from geothermal activity, point to apparent heat flow values of 60 to 100 mW/m^2. Until recently, the deepest well in Tibet was the 1650 m deep ZK308 well in the Yanbajing prospect (Cappetti and Wu, 1985), drilled through a shallow thermal outflow. The well stands almost entirely in Tertiary granites; the temperature profile at the bottom of the well is linear. If this gradient (36E-3°C/m) were controlled by conductive heat transfer, it is unlikely that the deeper heat flux would be greater than 90 mW/m^2.

Most of the heat flow data for Tibet previously published have been reduced for terrain effects assuming purely conductive heat transfer. However, it is known that, in steeper terrain, advective fluid flow can distort the temperature field of the brittle crust (Beck et al., 1989). A modelling study of the Zhangzhou low temperature system in South China (Yang Zhongke et al., 1990) has shown, for example, that even in moderate terrain a low temperature system can be set up by advective flow. At Zhangzhou, this flow sweeps heat from thick crustal granites into a fracture zone system within a large basin where deep fluids are discharged at boiling point temperature at the surface; neither high crustal heat flow nor crustal intrusions are required to maintain the Zhangzhou system. A gross permeability structure could be obtained by matching observed temperature gradients in wells of intermediate depths in the recharge and discharge areas. The gradients were lower in the mountains and significantly higher in the basin than those given by a 'normal' heat flow (Yang Zhongke et al., 1990).

If terrain-induced advective flow were significant in the steep valleys of Tibet, one could postulate that such flow would also produce a disturbed temperature field similar to that beneath the Zhangzhou prospect. In this case, most of the temperature gradients in wells standing in valleys should be disturbed (i.e., too high apparent heat flow values), and the widespread occurrence of thermal systems in the Himalayan Geothermal Belt might not necessarily be indicative of an anomalous hot upper crust but could be the result of advective flow.

Advective flow beneath a large valley in Tibet: the model

To assess the effect of advective flow we set up a model of an idealized large valley system in Tibet - which we call the 'Yanbajing Valley'. This large valley trends about NW-SW (see Fig. 2) for a distance of almost 200 km; geothermal systems are concentrated here. Figure 2 shows that there are three different systems in the valley which discharge fluids at boiling point temperature. The Yanbajing system is the largest of these (natural discharge of the order of 90 MW, according to Hochstein, 1988). It is probably the

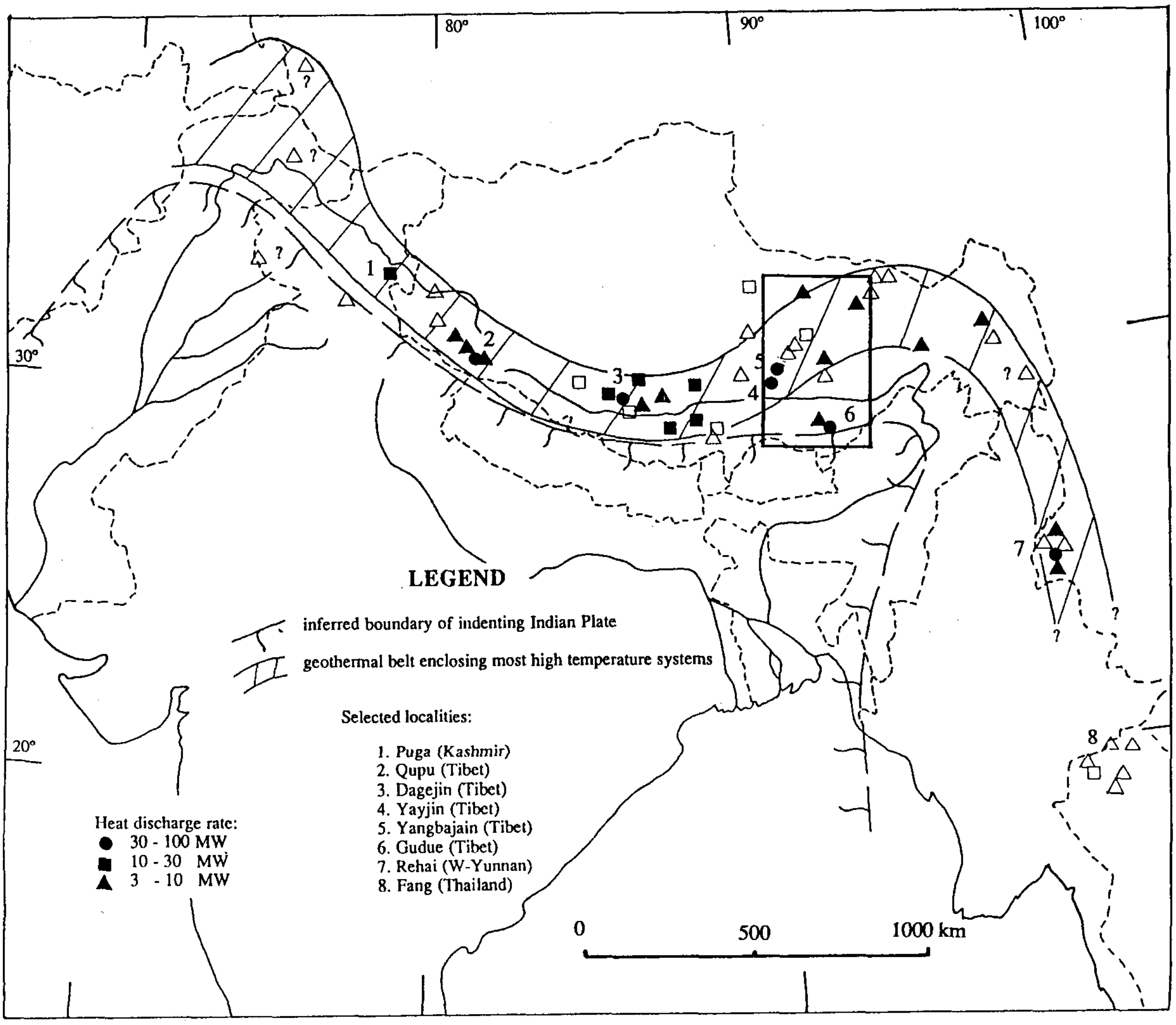

Fig. 1 Map showing the locality of geothermal systems in the Himalayan Geothermal Belt which discharge fluids close to boiling point temperature at the surface and which discharge heat at a rate greater than 3 MW. Solid symbols refer to high temperature systems (cation equilibrium temperatures greater than 200°C); open symbols refer to intermediate temperature systems (equilibria temperatures between 150 and 200°C). Low temperature systems are not shown. The approximate area covered by the map shown in Fig. 2 is framed.

largest geothermal system in Tibet. The valley is bounded in the NW by the Nyanchen Thanglha mountain range, with summit heights typically between 6500 and 7000 m; in the SE lies the Tang mountain range, with summit heights between 5500 and 6300 m elevation. The valley floor is at 4250 m elevation at Yanbajing and up to 4400 m elsewhere.

A smoothed two-dimensional topographic section was constructed for profile A-A' shown in the lower part of Fig. 3. From our own field observations in 1986 we constructed an inferred groundwater level for the whole section. The level was constrained by that of mountain creeks with continuous annual flow and high level springs. The configuration of saturated rocks was approximated by a sequence of slightly permeable, horizontal layers. The effect of a glacial cover in the valley was neglected. All rocks above the inferred piezometric level were assumed to be dry.

Since the temperature of the high springs is close to the mean annual temperature at Yanbajing (about 3°C), the piezometric level is the upper constant pressure and constant temperature boundary of the model. It was assumed that this boundary did not change significantly during the Quaternary (i.e. last 2 M yrs). Infiltration is maintained by melting of the snow pack.

Most rocks along the section are Lower Tertiary granites and volcanics; the metamorphic basement rocks (gneiss) of the Nyanchen Thanglha range are also intruded by Tertiary granites. It was assumed that the physical constants of all rocks exposed along the section are similar to those of the granites exposed in the valley. These have a mean (saturated) density of about 2650 kg/m^3, an average porosity of only 0.03, a mean (saturated) thermal conductivity of about 2.5 W/mK, and a thermal capacity of 1000 kJ/kg K.

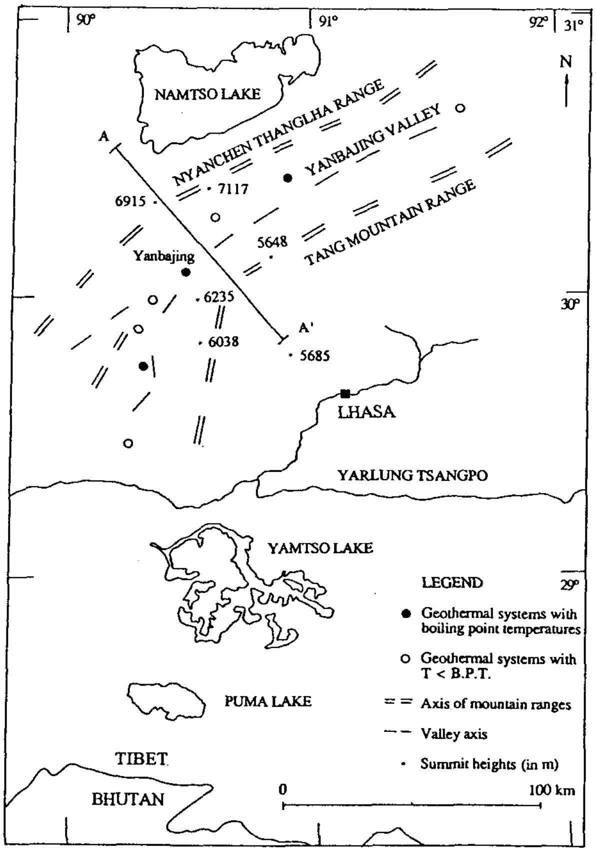

Fig. 2 Map showing the location of the extended Yanbajing Valley system; the locality of geothermal prospects is indicated by solid and open circles. The location of the section in Fig. 3 is shown by profile A-A'. Shown also are the locality of the two large lakes south of the Yarlung Zangpo Valley where heat flow studies have been conducted.

In an earlier, unpublished, modelling study of the outflow structure of the Yanbajing system (UNDP project CPR/81/011), which modelled natural state condition, an average isotropic permeability of 1 millidarcy (1 mD = 10^{-15} m^2) had been used for the granite basement (G. Cappetti, pers. comm. 1986).

Since the physical parameters of the granites in the Yanbajing Valley are similar to those of the Mesozoic granodiorites in the Zhangzhou prospect (Yang Zhongke et al., 1990), we adopted the crustal permeability structure of the Zhangzhou catchment to model the advective flow for the section shown in Fig. 3. Initially, we therefore used a structure with a permeability $k_z = 0.5$ mD and $k_{x,y} = 1$ mD for all rocks lying above the level of 3000 m, and $k_z = 0.2$ mD, $k_{x,y} = 0.5$ mD for all rocks between 3000 m and sea level. Since we were mainly interested in assessing the advective effects in shallow levels, the permeability structure of rocks below sea level was neglected (i.e. $k_z = k_{x,y} = 0$ below sea level). The model therefore extends for another 2 km below the bottom level of the section shown in Fig. 3. The advective flow was simulated by using a modified MULKOM program (Pruess, 1983). The initial temperature field was that given by conductive heat transfer, assuming a deep crustal heat flux of 90 (60) mW/m^2 at sea level. By using increasing time steps, the effects of advection were monitored until almost steady-state temperatures were obtained (≥2 M yr). The modelling procedure was the same as that described by Yang Zhongke et al. (1990).

Results

Results of the simulation are shown in Figs. 3 and 4. The resulting temperature field, assuming a deep crustal flux of 90 mW/m^2, is shown in the lower part of Fig. 3. Advection has caused a temperature 'plume' beneath the valley; the shaded area in the model outlines the temperature field where temperatures are significantly greater than those produced by conductive transfer. Crustal temperatures beneath the mountain ranges are depressed. The anomaly extends down to sea level.

Temperature gradients at a depth of 250 m beneath the inferred water table, [G_{90} (-0.25)] curve in upper part of Fig. 3, vary from 10E–3 °C/m) (mountain range) to 95E–3 °C/m (valley), and correspond to an apparent heat flux of 25 and 240 mW/m^2 respectively. The effect of advective convection is more than half an order of magnitude greater than the terrain effect for a conductive setting. The advective effects decrease if the magnitude of deeper heat flux is less. For a flux of 60 mW/m^2, the gradients [G_{60} (–0.25) in Fig. 3] attain values of 8E–3 °C/m beneath the mountain ranges, and about 55E–3 °C/m beneath the valley. The resulting gradients are therefore not linearly proportional to the magnitude of crustal heat flux, even for rocks with such a low permeability.

If the convective 'plume' beneath the valley were intersected by a deep-reaching fracture zone, similar to that which we modelled for the Fuzhou system (Hochstein et al., 1990), low temperature systems would develop, leading to a further distortion of the temperature field in the upper crust. Using the analogy of the Zhangzhou study, one can infer that most of the systems in the Yanbajing Valley developed as fracture zone systems within a temperature plume beneath the valley.

The problem of obtaining representative heat flow values from temperature profiles in wells in the valley is indicated by the profiles shown in Fig. 4. It can be seen that the temperature gradients (G_{90} and G_{60} in Fig. 4) decrease continuously with depth without reaching constant values. For depths greater than 1.7 km, these gradients show an 'overshoot' pattern, attaining even lower than 'normal' values, where 'normal' refers to the undisturbed conductive gradient (i.e. 36E–3 °C/m for G_{90} and 24E–3 °C/m for G_{60}).

Since the permeability of the outcropping rocks could be lower than that assumed for the initial model, we also assessed the effects of advective flow for surface rocks of low permeability ($k_z = 0.2$ mD, $k_{x,y} = 0.5$ mD down to 3000 m). The resulting temperature changes in all blocks are small and are only a few centigrade lower at 2 km depth than those shown in Fig. 4, thus indicating that most of the advective flow occurs below the 3000 m level. This finding is similar to that of a sensitivity analysis of the permeability structure beneath the Zhangzhou prospect (Yang Zhongke et al., 1990).

It is obviously a difficult task to obtain a representative value for the deeper flux from temperature measurements even in very deep wells if advection is significant. Curves

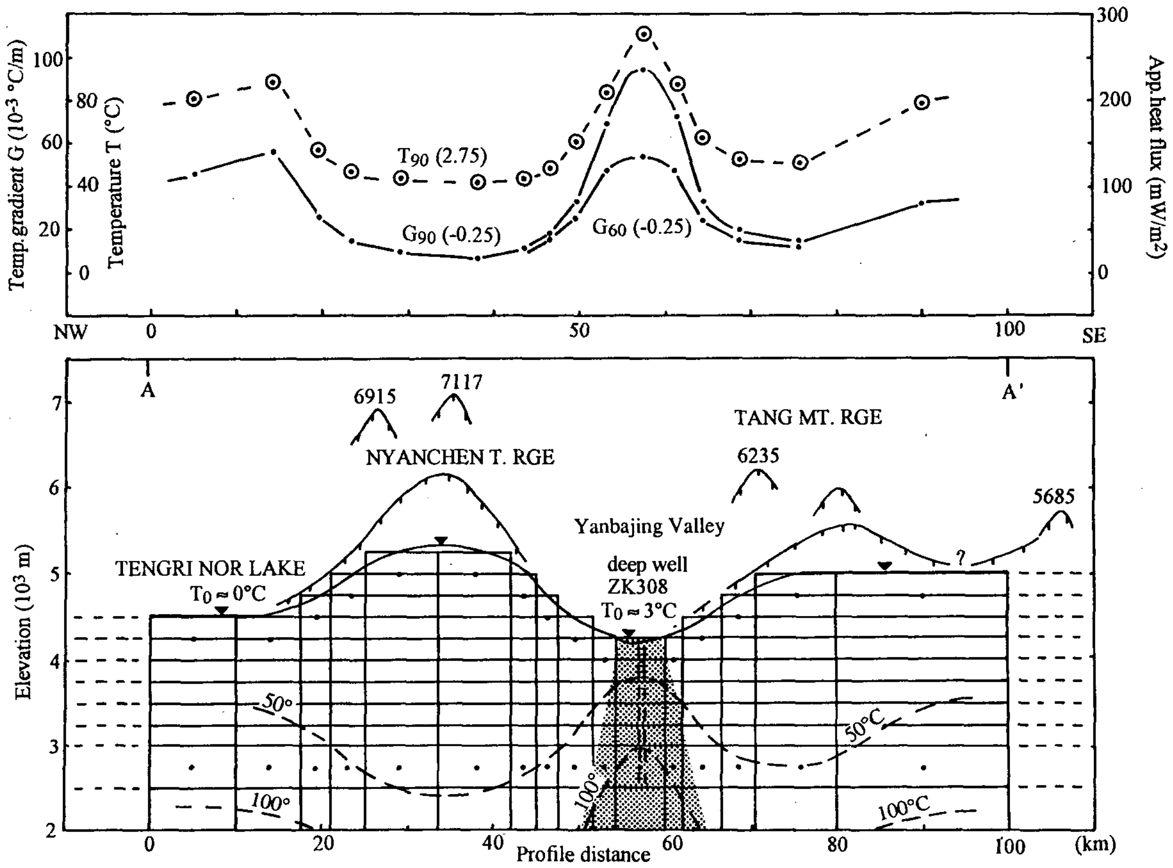

Fig. 3 Advective flow beneath the greater Yanbajing Valley. The section in the lower half shows the two-dimensional topographic model and the block structure of the saturated rocks. The lower part of the model which extends to sea level is not shown. The temperature contours (50°C, 100°C) in the block model refer to computed temperatures using a deeper crustal heat flux of 90 mW/m^2; the temperatures in the shaded plume are all greater than those produced by conductive heat transfer. The curve G_{90} (–0.25) in the upper half refers to the stable temperature gradient at a depth of 0.25 km beneath the water table based on a model with a deep crustal flux of 90 mW/m^2; the curve G_{60}(–0.25) refers to similar data but for 60 mW/m^2. The upper curve T_{90} (2.75) denotes the temperature at a level of 2.75 km (flux 90 mW/m^2).

similar to those shown in Fig. 4, however, can be used to obtain an estimate of the deeper flux. The temperature profile for the bottom 500 m section of the deep ZK308 well at Yangbajing is linear, indicating a gradient of about 36E–3 °C/m at a mean depth of 1375 m. Assuming that this gradient is not significantly disturbed, and that the advective flow beneath the valley is similar to that of the model shown in Fig. 3, the deep gradient in well ZK308 indicates a value for the crustal flux within the range of 60 to 90 mW/m^2 (see Fig. 4).

Since the Lhasa Valley has a morphology similar to that of the valley shown in Fig. 3, one can also use the data in Fig. 4 to assess an approximate value for the deep heat flow in the Lhasa Valley. Shen (1989) observed a gradient of 36E-3° C/m near the bottom of the 500 m deep GEOTH. No. 2 well in the Lhasa Valley. Rocks in the Lhasa section are also (early) Tertiary granites. The position of this data point in Fig. 4 indicates that the deeper heat flux at Lhasa is either less than 60 mW/m^2 or that it is disturbed by significant local infiltration of permeable fractures.

Discussion

Modelling the effects of advective flow beneath a large valley in Tibet has shown that this flow can disturb the crustal temperature field. Advective flow results in a redistribution of crustal heat, causing the development of thermal 'plumes' beneath valleys and other depressions. Surface temperature gradients in valleys can attain values more than half an order of magnitude greater than those resulting from conductive transfer. Since, in the past, most heat flow measurements in Tibet have been made in wells standing in valleys, it is likely that the published data contain a systematic error. The effect of advective flow is difficult to reduce since one has to use an inferred crustal crustal permeability structure.

With respect to the questions raised in the Introduction, we believe now that there is no conclusive evidence for the assumption of an anomalously hot brittle crust beneath the Himalayan Geothermal Belt, or that the accumulation of geothermal systems in this belt supports the inference of (upper) crustal magma chambers. There is indeed no

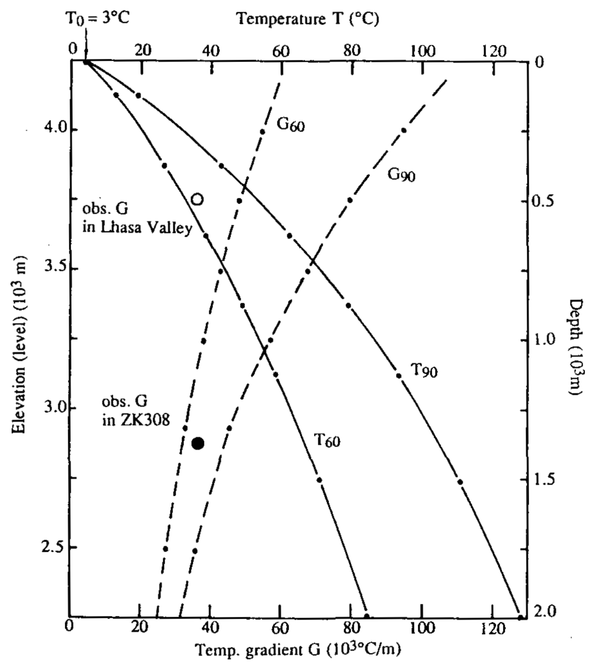

Fig. 4 Temperatures and temperature gradients within the central block lying beneath the Yanbajing Valley shown in Fig. 3. The temperature profiles T_{90} and T_{60} refer to temperatures produced by advection for a deeper crustal flux of 90 and 60 mW/m^2 respectively. The same applies for the temperature gradient profiles G_{90} and G_{60}. "Obs. G" refers to observed temperature gradients of selected wells in the Yanbajing and Lhasa valleys.

evidence for any volcanic activity in Tibet which is younger than 25 M yrs.

However, it is likely that the deeper, ductile crust is anomalously hot, as indicated by crustal seismic studies (i.e. lower shear wave velocities, anomalous attenuation, updomed level of the Curie point temperature). One can reconcile these findings with the results of this study by assuming that the brittle crust has been cooled by deep-reaching advective flow, probably reaching deeper than the flow pattern modelled in this study.

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