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# THERMAL CONSTRAINTS ON THE LATERAL EXTENT OF THE GEYSERS VAPOR-DOMINATED RESERVOIR

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## ABSTRACT

Recent well abandonment activities in the Unit 15 area of The Geysers geothermal field have provided a unique opportunity to investigate equilibrium thermal conditions to depths as great as 1.7 km near the southwestern boundary of the system. The southwestern boundary of The Geysers is characterized by a decrease in surface heat flow over a distance of less than 1 km from more than 400 $mW/m^2$ to less than 250 $mW/m^2$ outside the field. This boundary runs parallel to a series of northwest-trending faults which juxtapose various lithologic elements of the Franciscan complex. The new thermal data reveal a complex relationship between variations in near-surface (<200 m) heat flow, deep (>1 km) heat flow, and the top of the vapor-dominated reservoir (>1.5 km). The southwestern boundary of the reservoir at depth is characterized by an abrupt change in heat flow, and this change appears to correlate with the subsurface projection of mapped fault zones. Preliminary analyses suggest that advective heat transport along the fault zones may be significant, with heat flow in the units below these faults approximately equal to the surface heat flow found outside the reservoir. This lower value of heat flow presumably reflects the deep conductive heat source underlying The Geysers, whereas the higher value of heat flow above the reservoir reflects convective heat transfer within the vapor-dominated system. Modeling of the variation of heat flow with depth should yield detailed constraints on the geometry of this boundary.

## INTRODUCTION

According to White et al. (1971), one of the basic characteristics of The Geysers and other vapor-dominated hydrothermal systems is the presence of low permeability boundaries limiting recharge of liquid water into the higher permeability reservoir.

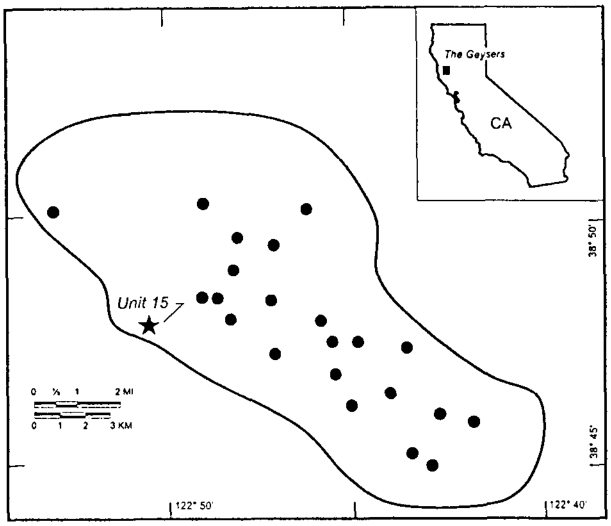

Fig. 1. Map of The Geysers region showing power plant locations (solid circles and star) and the producing limits of the steam field. Unit 15 is designated with a star.

The nature of these permeability barriers is generally tied to some combination of contrasting lithologies (perhaps due to faulting) and mineral precipitation from the fluids of earlier hydrothermal systems. Another aspect of this conceptual model is the potential for significant lateral heat flow between the convection-dominated reservoir and conduction-dominated country rock. With vapor-dominated conditions raising temperatures at the top of the convective system and lowering temperatures at the bottom of the system, there should be lateral heat transfer into and out of the reservoir (White et al., 1971).

Although heat flow through the caprock overlying The Geysers vapor-dominated reservoir has been the focus of detailed study (e.g. Urban et al., 1975; Thomas, 1986; Williams et al., 1993), comparatively little is know about the lithologic, structural, and hydrogeologic processes responsible for the location

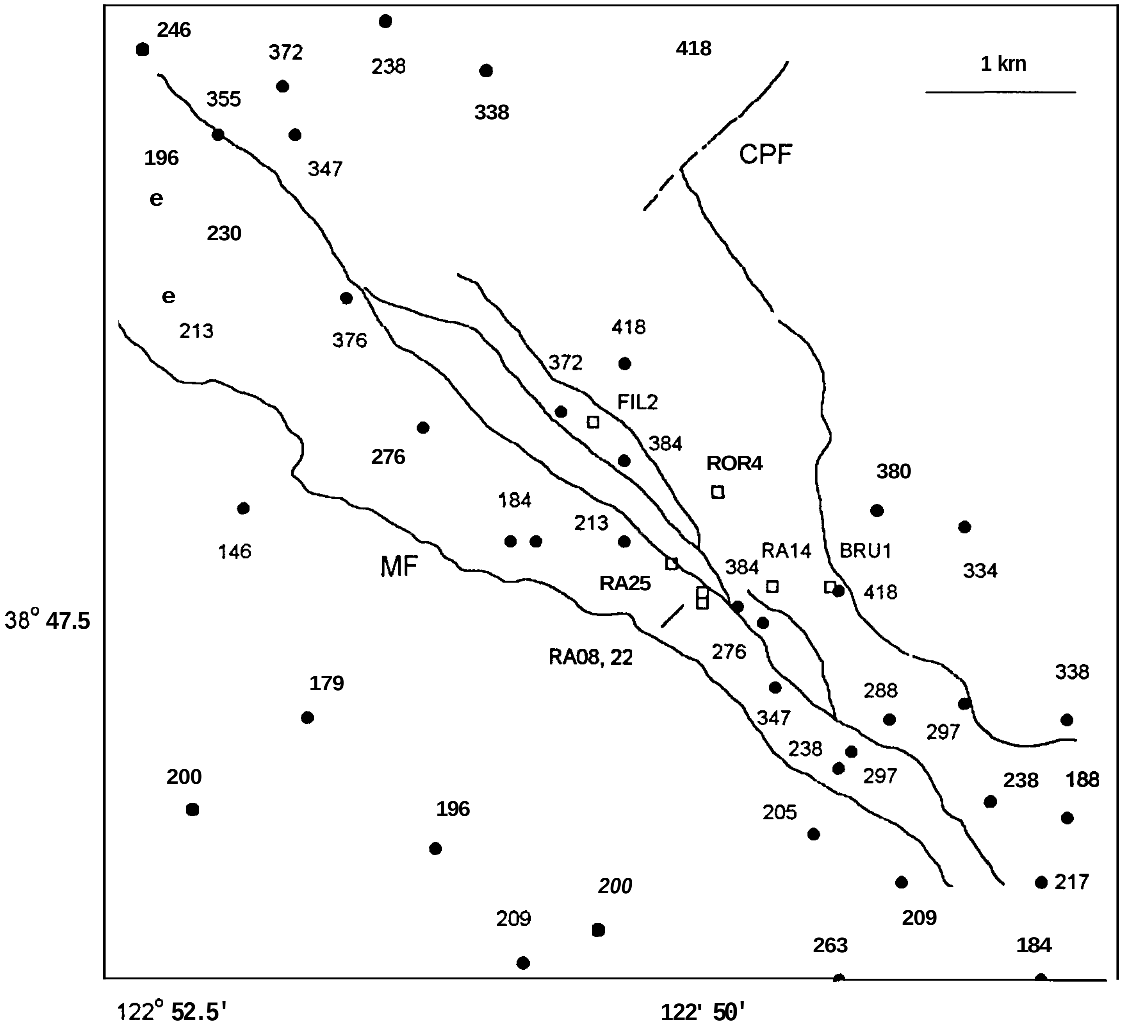

Fig. 2. Unit 15 area with mapped faults, shallow heat-flow measurements (solid circles) and idle production wells logged in this study (open squares). CPF is the Caldwell Pines fault and MF is the Mercuryville fault.

and maintenance of the lateral boundaries of the reservoir. Evidence obtained from within the producing limits of the field itself point to a combination of lithologic contrasts, faulting, and fracturing due to proximity to the felsite intrusive body as important components of the permeability of The Geysers system (e.g. Thompson, 1991). Presumably these same factors have led to the generation of the lateral boundaries as well.

One of the few comprehensive data sets indicative of subsurface thermal conditions outside the producing limits of the field is the large number of shallow, exploratory heat-flow and temperature-gradient holes (Thomas, 1986; Walters and Combs, 1991; Walters, 1995). As noted by Thomas (1986) and Walters and Combs (1991), these measurements effectively delineate the spatial limits of the reservoir, with heat flow exceeding 350 mW/m$^2$ over most of the producing area. In general, the thermal boundary of The Geysers is abrupt, with heat flow decreasing by 100 to 200 mW/m$^2$ over a distance of 2 km or less outside of the reservoir. This sharp thermal boundary is particularly well-defined at the southwestern edge of the field near the idled Unit 15 power plant (Figure 2). Here near-surface heat flow decreases from an average of approximately 400 mW/m$^2$ to less than 250 mW/m$^2$ over less than 1 km.

This decrease in heat flow not only corresponds to the edge of the vapor-dominated reservoir but also parallels the NW-SE trend of many mapped faults, including the Mecuryville Fault (McLaughlin, 1981). Although this thermal feature is consistent with a sharp-edged advective process, it is difficult to extrapolate these measurements to depth. Blackwell (1992) examined a similar feature along the southwestern edge of The Geysers near Pine Flat and Klau Mine (approximately 8 km southeast of Unit 15) and noted the apparent ambiguity between the deep thermal structure as extrapolated from near-surface measurements and the actual observations available from two deep exploratory wells.

From these and other studies, the basic questions about the nature of the reservoir boundaries can be summarized as follows. Is the reservoir boundary the result of decreasing fracture permeability in the reservoir graywacke, the juxtaposition of relatively impermeable rocks against permeable reservoir rocks, or the cooling effects of water flow in faults or fractures outside the reservoir at rates sufficient to suppress the development of vapor-dominated conditions? For all three possibilities the unknown factor is whether the absence of vapor-dominated conditions follows from either too much or too little permeability. We address these possibilities through the use of deep temperature data acquired from idle production wells in the Unit 15 area.

## DATA

During the period of rapid development of The Geysers in the late 1970's and early 1980's, a large number of wells were either drilled or deepened by GEO on the old Thermogenics property known as Unit 15. Economic difficulties led to a shut-in of the field in 1989, and the wells remained in a static condition until 1997, when the California Division of Oil, Gas and Geothermal Resources and the Environmental Protection Agency instituted a program of well abandonments. This provided a unique opportunity to acquire deep thermal data under near-equilibrium conditions, and in the spring and fall of 1997 the US Geological Survey ran precision temperature logs in four of the idle production wells. Although problems with wellhead corrosion, $H_2S$-rich gas, and bridged open hole sections limited access, temperatures were recorded to depths as great as 1.7 km. Taken together with the shallow heat-flow data, recorded steam entries and the intermediate-depth temperature data collected by Jamieson (1976), the new temperature profiles provide an invaluable look into the nature of The Geysers at depth.

Figure 3 shows the temperature data acquired in this study, along with those reported by Jamieson (1976). Temperatures were measured in either water (FIL2) or a mixture of air, gas and steam (RA14, RA22, RA25). Except for RA22, which was leaking potentially significant amounts of gas at the time of the survey, and the lower 600 m of RA14, which was disturbed by flow between two points in the borehole, all of the logs appear to represent equilibrium conditions. In confirmation of this, temperatures recorded by Jamieson (1976) in RA08 when plugged back and filled with water, are essentially indistinguishable from those recorded in the gas and air mixture of RA25, located a few hundred meters to the northwest on the same ridge top (Figure 2).

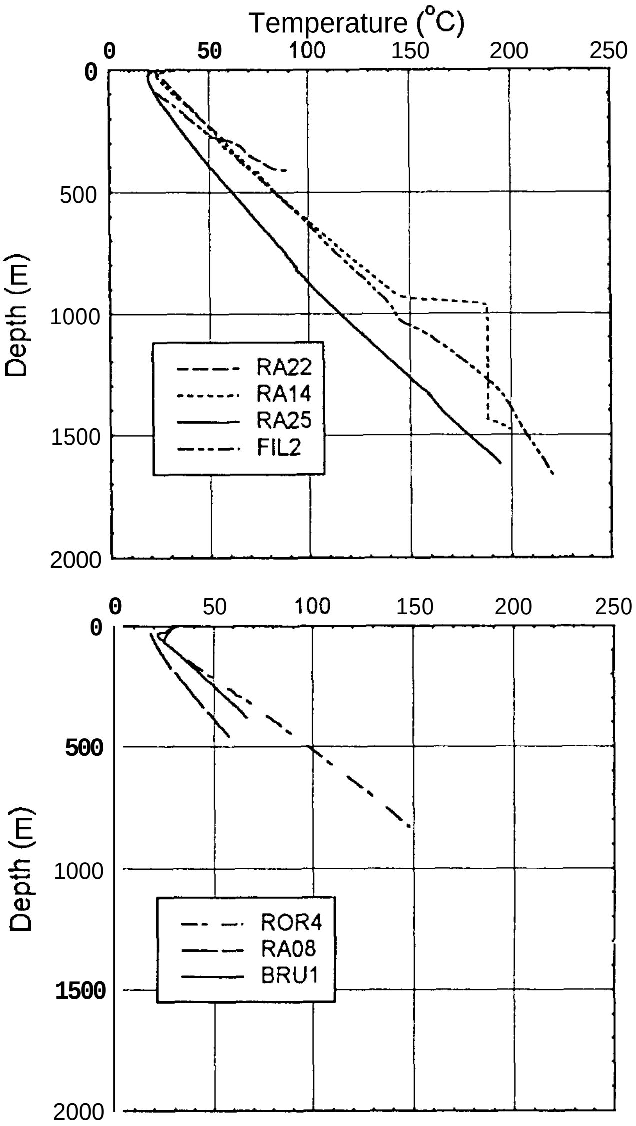

Fig. 3. Top - Temperatures recorded by the USGS in four wells in the Unit 15 area. Bottom - Temperatures reported by Jamieson (1976).

The primary feature of these logs is the large difference in gradient between the wells located to the northeast (RA14, ROR4, BRU1, FIL2) and those located to the southwest (RA25, RA08). Gradients in the upper 1 km of the northeastern wells range from 120 to 150 °C/km. Those in the southwestern wells range from 80 to 110 °C/km. Part of the difference in the shallow subsurface is related to the effects of topography, but this difference persists at depths below the point at which topography and microclimatic effect are no longer significant (approximately 1 km; see Jamieson, 1976 for a complete discussion of topographic corrections in this terrain).

## CONTRASTS IN TEMPERATURE AND HEAT FLOW

Figure 4 shows a southwest-northeast cross section of isotherms through the Unit 15 area. The most striking feature in this profile is the sharp dip in the isotherms to the southwest, with the offset increasing with depth. Between the locations of RA14 and RA22 the 50 °C isotherm deepens approximately 90 m over a distance of 300 m. By contrast, the 200 "C isotherm deepens by more than 300 m over the same 300 m distance.

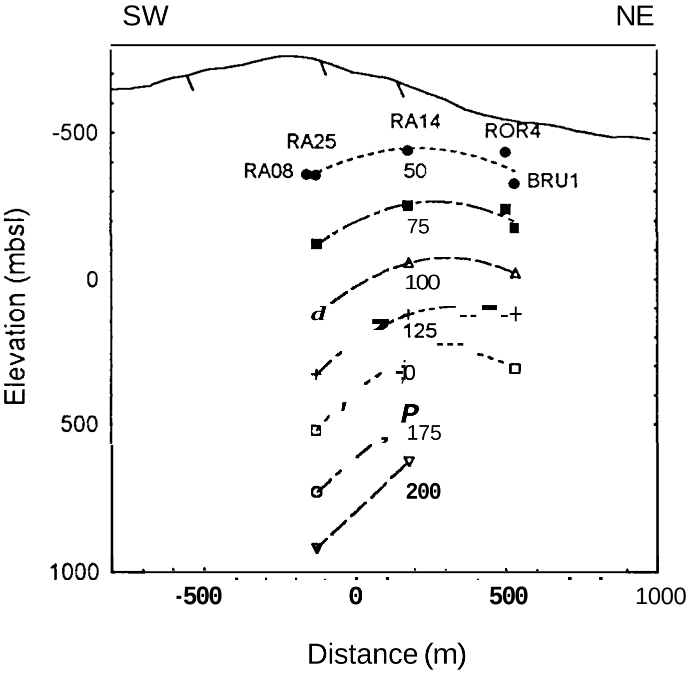

Fig. 4. Contoured isotherms located along a Southwest-Northeast section through Unit 15. Topography and mapped faults also indicated.

These variations in temperature are substantial and result in a lateral temperature gradient nearly as large as the vertical temperature gradient. The lateral gradient between RA14 and RA25 varies from 50 to 110 °C/km, in contrast to the measured vertical gradients of 70 to 150 °C/km. If heat transport in the caprock section is predominantly conductive, as a number of studies indicate (Urban et al., 1975, Jamieson, 1976; Walters and Combs, 1991; Williams et al., 1993), this result points to a large lateral component of heat transfer which may not reflect equilibrium conditions.

According to Hulen et al. (1997), trapping temperatures and pressures of fluid inclusions in well samples from The Geysers indicate that the current vapor-dominated conditions may have developed at about 260 ka at a temperature near 290 °C. The Unit 15 heat-flow study of Urban et al. (1975) indicates that the top of the present 240 "C vapor-dominated reservoir is in thermal equilibrium with the ground surface, establishing its age as at least 20 ka. Although vapor-dominated conditions may have taken some time to expand out from the Sulfur Bank area studied by Hulen et al. (1997) to the Unit 15 area, it is reasonable to consider whether the strong lateral temperature gradient measured across the Unit 15 wells could be a transient feature inherited from the formation of The Geysers vapor-dominated system. An important component in this analysis is the lateral variation in conductive heat flow.

Figure 5 shows a southwest-northeast profile of heat flow through Unit 15 as measured in shallow temperature-gradient holes (typically less than 200 m deep) and selected depths in the idle production wells. Although there is significant variability (most likely due to the limitations of applied topographic and microclimatic corrections), there is a substantial decrease in near-surface heat flow from more than 400 mW/m$^2$ to approximately 200 mW/m$^2$ over a distance of less than 1 km. Measurements at a depth of 500 m follow a similar, but more subdued, trend, decreasing from more than 400 to about 300 mW/m$^2$. Finally, with the exception of the 1500 m measurement in FIL2, it is difficult to tell whether heat flow at depths of 1000 m and 1500 m varies or remains constant.

These observations are consistent with those of Blackwell (1992), who pointed out the existence of a "shoulder" of intermediate heat flow between the high values directly over the reservoir and moderate values approximately 2 km distant. In the Unit 15 area the "shoulder" appears as a 1 km-wide region with heat flow varying between 200 and 300 mW/m$^2$ (Figures 2 and 5). This "shoulder" could be interpreted as enhanced vertical heat flow due to significant lateral heat transport from the reservoir to the northeast. However, if the current vapor-dominated conditions did form at 260 ka, there is more than enough time (approximately 13 times the thermal time constant of the overlying caprock) for the sharp thermal boundary to smooth out in equilibrium with the surroundings. In the absence of a youthful origin, this sharp boundary can only be maintained by significant advective transport of heat.

## THERMAL EVIDENCE FOR FLUID FLOW

Another important feature of the data shown in Figures **3** and 5 are the abrupt changes in gradient (and consequently heat flow) observed in wells RA25 and FIL2.

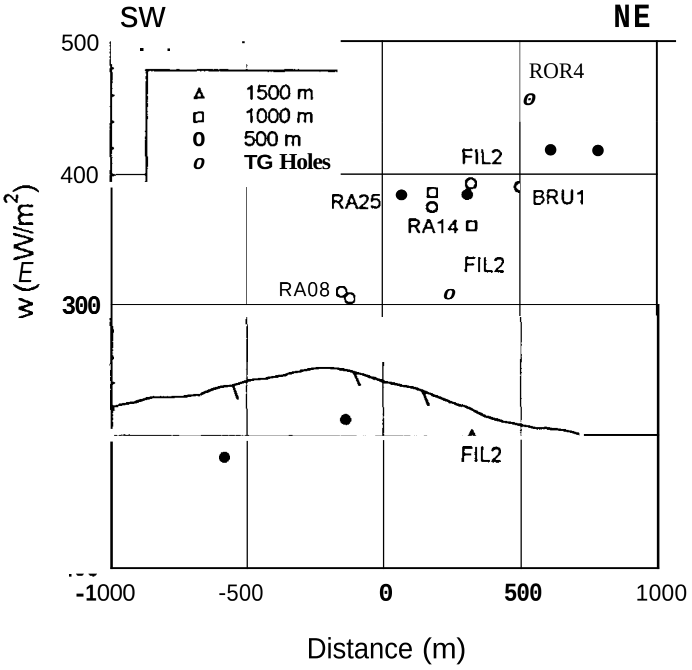

Fig. 5. Heat flow along the same profile shown in Figure 4 for temperature-gradient holes and three selected depths in the deep production wells.

In RA25, gradients increase from 105 °C/km to 130 °C/km over the depth range from 700 to 800 m. There are no lithologic changes indicative of a conductivity change, but drilling records indicate a fault intersecting the wellbore at this point. The change in gradient equates with an increase in heat flow of appproximately 70 mW/m$^2$, and the correlation of this change with an intersecting fault is consistent with a reduction in heat flow due to the downward flow of ground water. This is supported by oscillations in the temperature log that are consistent with water moving in the annulus behind the casing between 700 and 800 m. The nearly identical thermal conditions in the upper part of RA08 suggest that this downward flow could be along a fault running parallel to those mapped on the surface (Figure 2). The difficulty of projecting the surface traces of faults at The Geysers into the subsurface (see discussion by Thompson, 1992) precludes identifying this fault with any particular surface feature, but the possible downward flow is consistent with the topographic gradient from the Unit 15 ridge top down to Big Sulfur Creek to the northeast. If this downward flow of water extends out into the region between RA25 and RA14, it may provide an advective explanation for the large lateral contrast in temperature.

A simple model for the contrast in heat flow introduced by fluid flow along an inclined fracture was derived by Lewis and Beck (1977). If the fluid flow has persisted for enough time to approach thermal equilibrium, the difference in conductive heat flow across the fracture is given as

$$\Delta q = WC_f\Gamma\sin(\theta) \qquad (1)$$

where W is the mass rate of flow per unit length of the fracture, $C_f$ is the heat capacity of the fluid, $\Gamma$ is the undisturbed geothermal gradient, and $\theta$ is the dip of the fracture plane. For a fracture dipping at 75° and an observed difference in heat flow of about 50 mW/m$^2$, a flow rate of at least 4 m/yr would be required (see a similar analysis by Williams et al., 1997). With annual precipitation in this region of approximately 1 m/yr and only a modest fraction of this penetrating the subsurface, substantial focusing of the natural topographically-driven ground-water flow would be required to account for the observed contrast in heat flow.

FIL2 exhibits the opposite change, with a gradient of 130 °C/km above 1300 m dropping to 75 °C/km below. This change in gradient corresponds to a fault-bounded lithologic change to more argillite-rich graywacke. However, according to the thermal conductivity studies of Jamieson (1976), Thomas (1986), Walters and Combs (1992), and Williams et al. (1993), the increasing argillite content should lower the effective thermal conductivity and thus magnify the apparent 140 mW/m$^2$ decrease in heat flow.

A possible understanding of thermal conditions in FIL2 comes from its location and the presence of water (rather than steam) at depth. FIL2 and many other wells of the Unit 15 area are characterized by an anomalously high (> 5000 ppmw) noncondensible gas content (Walters et al., 1996). This is an exception to the overall pattern at The Geysers, where high gas contents are generally limited to the Northwest Geysers, with the Caldwell Pines fault acting as a barrier between the two portions of the field (Figure 2; Walters et al., 1996). One consistent explanation for the composition of the steam in Unit 15 and the vertical variation in heat flow with depth in FIL2 is a truncation of or permeability "gap" in the Caldwell Pines fault, with gas and steam from the Northwest Geysers moving across to Unit 15. In this scenario, the fault penetrated by FIL2 is a pathway for fluid moving up from the vapor-dominated reservoir. Below this fault, the well trends away from the reservoir and the high permeability fractured graywacke. The boundary of the system in this case is a fault-bounded lithologic contrast with fluid moving up the fault.

## CONCLUSIONS

The new deep temperature data from Unit 15 demonstrate a persistence of spatially variable thermal conditions at depth consistent with the variations captured by near-surface heat flow measurements. Most prominent among these variations is the pronounced gradient in temperature across the southwest boundary of the field. This gradient may have a conductive origin, but the reported age of the vapor-dominated system and the observed disturbance of heat flow by flow along faults indicate an advective source. Although detailed numerical modeling is required, these preliminary results suggest that the boundary of the reservoir may be determined by a combination of distance from the heat source and the abundant flow of liquid water through permeable faults and fractures.

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