Geology

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Geology 2012;40;119-122
doi: 10.1130/G32565.1

Notes

THE GEOLOGICAL SOCIETY OF AMERICA

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ABSTRACT

Postseismic decrease in groundwater temperature was documented on the upper rim of a large alluvial fan near the epicenter of the 1999 M_w 7.5 Chi-Chi earthquake (Taiwan). We use a model of coupled heat transport and groundwater flow, constrained by documented water-level changes, to interpret this change. We show that groundwater temperature is sensitive to earthquake-induced flow and the observed temperature decrease may be explained by increased groundwater discharge due to earthquake-enhanced vertical permeability. The result implies that heat flow near active mountain fronts may be lowered by recurrent earthquakes.

INTRODUCTION

Heat flow provides important information for deciphering tectonic processes, yet the interpretation of heat-flow data requires considerable care. Groundwater flow can significantly affect the subsurface temperature (e.g., Forster and Smith, 1989; Ingebritsen et al., 1989; Brumm et al., 2009). Because large earthquakes can release large quantities of groundwater (e.g., Muirwood and King, 1993; Rojstaczer et al., 1995; Manga et al., 2003; Wang et al., 2004a), we may expect that the subsurface temperature will be affected. On the other hand, there have been few studies that report changes of groundwater temperature after earthquakes. Existing reports include coseismic changes of temperature in a hot spring on the Izu Peninsula, Japan (Mogi et al., 1989), and changes in temperature in shallow groundwater in Italy (Quattrocchi et al., 2003) and in some submarine geothermal systems (e.g., Sohn et al., 1998). Here we report widespread decreases of groundwater temperature following the 1999 M_w 7.5 Chi-Chi earthquake (Taiwan) over the upper rim of an alluvial fan near the epicenter. We use a model that couples heat transport and transient groundwater flow, together with documented water-level changes, to interpret the changes in groundwater temperature.

OBSERVATIONS

Taiwan is a young mountain belt formed by the oblique collision between the Chinese continental margin and the Luzon Arc on the Philippine Sea plate since 5 Ma (Fig. 1A). The mountain belt extends nearly north-south and is bordered on the west by a west-vergent thrust belt (Fig. 1C), which in turn thrusts over a large alluvial fan in central Taiwan (the Choshui River alluvial fan; Figs. 1B and 1C). A network of 70 evenly distributed hydrological stations, with 188 monitoring wells to depths between 50 and 300 m, was installed on the alluvial fan (Fig. 1B). Well logs show that the alluvial fan consists of unconsolidated Holocene to Pleistocene sands and gravel separated by fine silts and marine mud, overlying a basement of consolidated Cenozoic sedimentary rocks (Fig. 1C).

After the 1999 Chi-Chi earthquake, changes in temperature and water level were documented in these wells. The changes in water level were reported in previous studies (e.g., Chia et al., 2001; Wang et al., 2001; Wang and Chia, 2008). Here we focus on the change in groundwater temperature. We further restrict the study to a group of wells (Table 1) located on the upper rim of an alluvial fan near the ruptured fault of the earthquake (Fig. 1B, between two thick dashed lines) where a drop in the groundwater temperature was documented after the earthquake. Farther to the west, wells showed, instead, increases in the groundwater temperature; these, however, are not included in the present analysis.

Temperature of groundwater was measured during routine well maintenance, using an Aqua TROLL200 manufactured by In Situ Inc., with an accuracy of ±0.1 °C and relative precision of ±0.01 °C. Data are thus available only at discrete times separated by intervals of several months or longer. In the present study, we use only measurements made within a year before and after the earthquake, because, for longer time separations, factors unrelated to the earthquake (i.e., changes in surface temperature) may influence the measured temperature.

Within this time interval, only one measurement was made in the wells before the earthquake (Table 1) and at most, two measurements after the earthquake (Fig. 2A). Notwithstanding the lack of continuous data, we believe the difference between the preseismic and the postseismic temperatures may represent the effect of the earthquake for the following two reasons: (1) All temperatures after the earthquake showed a consistent

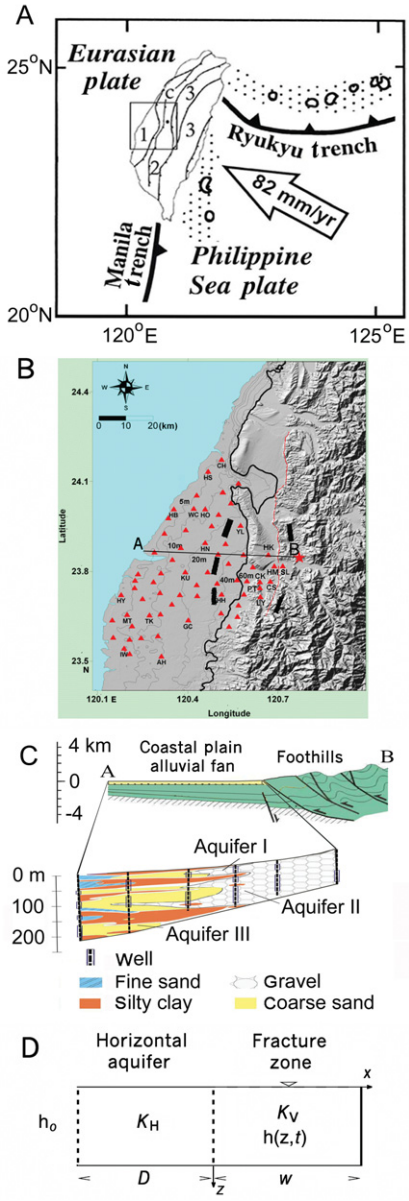

Figure 1. A: Location map of study area (square box) in Taiwan. Also shown are major structural and tectonic features: 1—coastal plain; 2—foothills; 3—central ranges; c—Chelungpu fault. Dot in box represents Chi-Chi earthquake epicenter; dotted pattern off Taiwan shows submerged volcanic arcs. B: Hydrological monitoring wells (red triangles) on the Choshui River alluvial fan. Red star shows epicenter of the 1999 Chi-Chi earthquake; red line shows surface trace of the ruptured fault. Wells labeled with station names are those with documented postearthquake temperature changes: Those located between two thick dashed black lines all documented negative changes; those farther to the west all documented positive changes. Continuous black line shows thrust front of the Taiwan fold-and-thrust belt. 5 m, 10 m, 20 m, and 40 m refer to contour elevations above sea level. Line AB shows location of cross section in C. C: Schematic cross sections showing subsurface geology along line AB. The Choshui River alluvial fan (in yellow) overlies consolidated basement rock (in green). Enlarged lower diagram shows geology of alluvial fan, where aquifers I, II, and III refer to aquifers separated by aquitards. D: Schematics of conceptual model of fracture zone with effective vertical conductivity K_V and horizontal aquifer with effective conductivity K_H (see text).

TABLE 1. TEMPERATURE IN WELLS (FIG. 1B) BEFORE AND AFTER THE CHI-CHI EARTHQUAKE

Wells	Surface elevation (m)	Temperature logger depth (m)	Temperature 1999-2/3 (°C)	Temperature 1999-11/12 (°C)	Temperature difference (°C)
PT1	297.8	171	24.0	22.99	–1.0
CK1	113.6	80	25.4	24.80	–0.6
CK2	113.3	159	25.0	24.72	–0.3
CS1	151.2	81	24.6	24.39	–0.2
CS2	151.2	171	25.1	24.72	–0.4
HH2	36.7	110	25.5	24.96	–0.5
HH3	36.6	218	25.9	25.19	–0.7
HH4	36.7	288	26.4	25.93	–0.5
YL2	26.7	106	24.4	23.94	–0.5
YL3	26.7	137	24.5	24.01	–0.5
YL4	26.7	189	24.8	24.20	–0.6
SL1*	179.3	14	24.6	24.08	–0.5

*SL1 well is located on the upper plate of the ruptured Chelungpu fault (Figure 1B) and not on the same structural-stratigraphic unit as the other wells (Figure 1C). Thus, it is not included in the analysis

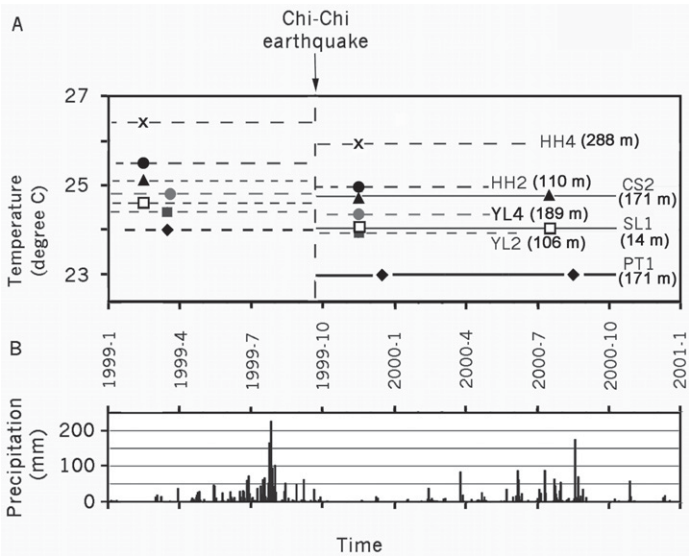

Figure 2. A: Temperature in wells from 1 January 1999 to 1 January 2001. Solid lines show wells with two measurements after the earthquake; dashed lines show wells with one measurement before or after the earthquake. Refer to Figure 1B for well locations. B: Daily precipitation near the YL well. Notice that the postseismic measurements at each of the CS2, SL1, and PT1 stations show the same value, even though the first measurement was made during the dry season while the second was made during the rainy season.

decrease (Table 1), and (2) in wells with two measurements after the earthquake (CS2, SL1, PT1), temperatures are the same in the two measurements (Fig. 2A), even though the first was made during the dry season and the second during the rainy season (Fig. 2B), showing that, at the depth of the temperature gauges (Table 1), the measurement was not affected by seasonal changes in surface temperature or recharge.

MODEL

Field surveys near the ruptured fault revealed numerous subvertical fractures in the unconsolidated sediments after the Chi-Chi earthquake (Lee et al., 2002). Wang et al. (2004a) suggested that enhanced vertical permeability may have occurred in the crust near the epicenter, causing increased groundwater discharge from the nearby mountains—a suggestion supported by a sudden downpour in a tunnel beneath the foothills after the Chi-Chi earthquake. The horizontal permeability, on the other hand, changed little, as the recession constant of stream discharge before and after the earthquake did not change (Wang et al., 2004a; see also Manga, 2001). Thus for the present study, we consider only the evolution of temperature in the vertical direction, approximated by solving the advection-diffusion equation

$$\frac{\partial T}{\partial t}=\frac{\partial^2 T}{\partial z^2}-q_z\frac{\partial T}{\partial z} \tag{1}$$

subject to appropriate boundary and initial conditions. Here κ is thermal diffusivity, q_z is Darcy's flow in the vertical direction, $\gamma = c_w r_w / c_b r_b$, c is specific heat, ρ is density, and the subscripts w and b refer to water and bulk properties, respectively.

For boundary conditions, we assume a constant geothermal gradient at the base of the alluvial fan and a constant temperature at the surface. The exact value of the latter is immaterial here because we are only concerned with the change in temperature after the earthquake. The geothermal gradient over Taiwan's coastal plain is relatively high (Hwang and Wang, 1993); we assume a constant geothermal gradient of 40 °C/km at the base of the alluvial fan.

For modeling the groundwater flow, we represent the fracture zone by an unconfined aquifer overlying a basement (Fig. 1D). This representation differs from the usual treatment of unconfined aquifers in that flow now occurs in the vertical direction, rather than in the horizontal direction; thus, the usual Dupuit's approximation does not apply. Groundwater flow in the vertical direction is governed by Darcy's equation

$$Q=-wK_V\frac{\partial h}{\partial z}, \tag{2}$$

where K_V is the vertical hydraulic conductivity of the fracture zone, w is the width of the fracture zone across which fluid is being discharged, h is the hydraulic head, and z is depth. Consideration of mass conservation leads to the following flow equation in the vertical direction:

$$\frac{S_y}{L}\frac{\partial h}{\partial t}=K_V\frac{\partial^2 h}{\partial z^2}-\frac{q_x}{w}, \tag{3}$$

where S_y is the specific yield, defined as the change of groundwater volume in a column of the unconfined aquifer of unit cross-sectional area per unit change of head; L is the saturated thickness of the fracture zone, considered constant to be consistent with the adopted boundary condition (next paragraph); and q_x is the leakage from the fracture zone to subhorizontal aquifers in the alluvial fan (Fig. 1C). Increased discharge from the fracture zone leads to increased recharge of aquifers, which, in turn, leads to increased discharge to the left boundary (Fig. 1D); the latter may correspond to where the observed warming occurred (Fig. 1B).

In humid mountainous regions such as Taiwan, the water table is topography-controlled and, in the foothill area, it is generally shallow and relatively constant (Gleeson et al., 2011). For this reason, we adopt the boundary condition that the water table is at the surface, i.e., $h = 0$ at $z = 0$. We further assume that the basement beneath the alluvial fan is impervious, i.e., $\partial h/\partial z = 0$ at $z = L$, because consolidated basement rocks are usually much less permeable and mechanically much stronger than unconsolidated sediments.

Modeling parameters, listed in Table 2, are inferred from well logs, pump tests, and recession analysis of the postseismic water level in wells, as explained in the GSA Data Repository[1]. The method for calculating T is also given in the GSA Data Repository. Flow in the fracture zone is driven by the difference between the hydraulic head $h(z, t)$ in the fracture zone and that at the discharge end of the aquifer. Before the earthquake, $K_V = K_{Vi}$, and groundwater flow in the aquifer was at a steady state. After the

[1]GSA Data Repository item 2012033, explanation of methods, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

TABLE 2. REFERENCE MODEL PARAMETERS

Horizontal conductivity, K_H	10^{-4} m/s
Initial vertical conductivity, K_{Vi}	10^{-8} m/s
Final vertical conductivity, K_{Vf}	10^{-5} m/s
Specific yield, S_y	0.2
Distance between fracture zone and point of discharge, D	10 km
Width of fracture zone, w	10 km
Saturated thickness of fracture zone, also basement depth, L	300 m
Head at point of discharge, h_o	–100 m

earthquake, $K_V = K_{Vf}$; both the recharge from the surface and the discharge from the fracture zone increased in response to the enhanced vertical permeability (Wang et al., 2004a). The system dynamically adjusts itself until the head reaches a new equilibrium state. Density and viscosity of pore water are assumed constant because the range of depth in this study is small. Even though this model is highly simplified, similar models (e.g., Roeloffs, 1998; Manga, 2001; Manga et al., 2003; Brodsky et al., 2003; Montgomery and Manga, 2003; Wang et al., 2004a, 2004b; Manga and Rowland, 2009) have been shown to agree with data and to characterize the first-order hydrological system response to earthquakes.

RESULTS AND DISCUSSION

Temperature for the reference model after the earthquake (relative to the surface temperature) is given in Figure 3A. Temperature gradient decreases to zero at shallow depth from an initial gradient of ~40 °C/km, and the range of depth with zero gradient increases with time. In comparing model results with observation, we note that the results for a single set of parameters are not expected to yield all the well data because, in the natural setting, sediment properties vary from well to well, affecting the magnitude of the temperature changes.

Figure 3B shows the calculated change in temperature for the reference model (Table 2). Because most data were collected about two months after the Chi-Chi earthquake, we test the model fit by comparing data with the curve from the 60th day after the earthquake. This curve fits the group of data points 2–7, but not the other points. To examine sensitivity of the model to the vertical permeability, we increase the value of K_{Vf} from 1×10^{-5} to 3×10^{-5} m/s, while keeping the other parameters the same as in the reference model. This minor change in K_{Vf} results in an increase in both the magnitude of the temperature change and the range of affected depths by a factor of ~2 (Fig. 3C), leading to a good fit to data points 8–10 on the 60th day after the earthquake. Given that the difference between the two models is minute compared with the uncertainty in K_{Vf}, we conclude that the reference model is consistent with observation. The model is much less sensitive to K_H and S_y; the results are not shown here for the sake of space.

Several recent studies show that, after earthquakes, the enhanced permeability gradually returns to the preseismic value (e.g., Claesson et al., 2007; Elkhoury et al., 2006), probably by biogeochemical processes that reclog fluid passageways opened during the earthquake. Recovery of earthquake-enhanced permeability may affect the postseismic groundwater flow. For an order-of-magnitude evaluation of this effect, we assume a "relaxed model" in which the enhanced permeability recovers exponentially with time, i.e., $K_{Vf} = K_{Vi} + K_{Vfo}\exp(-t/\tau)$, where K_{Vfo} is the enhanced vertical permeability right after the earthquake and τ is the relaxation time. With $\tau = 2$ yr, the calculated temperature change (Fig. 4A) shows a slight reduction from the reference model in the magnitude of temperature changes and the range of affected depths, but the curve for the 60th day after the earthquake fits the data points as well as that in the reference model. Thus the two models cannot be differentiated by the available data. On the other hand, the model with $\tau = 10$ d (Fig. 4B) is clearly ruled out by the observational data.

The postseismic temperature change reported here is not a single isolated event in time, but one of numerous events in the geologic past. In view of the linearity of the differential equation 1, each earthquake-induced temperature change may be calculated independent of the others, and the total change is the algebraic sum of the individual changes. Figure 4C shows the long-term change of groundwater temperature after a single earthquake (for the model with $\tau = 2$ yr). Temperature continues to decrease until 10 yr after the earthquake because, even after several decay times, K_{Vf} is still much greater than K_{Vi}. Shallower than ~250 m, temperature rises with time 10 yr after the earthquake, but, deeper than 250 m, it continues to decrease until 200 yr after the earthquake (Fig. 4C). In all cases, the temperature gradient at the surface is lower than that before the earthquake, even 300 yr after the earthquake. Given that the recurrence interval of large earthquakes in western Taiwan is several hundred years, we infer that heat flow near the active mountain fronts may be lowered by the accumulated effect of numerous earthquakes.

The postseismic temperature change reported here cannot be isolated in space. The observed cooling and warming of groundwater in different parts of the alluvial fan (Fig. 1B) may reflect the removal and addition of heat in the same groundwater transport system. Analysis of this problem, however, is outside the scope of this study.

Because groundwater temperature is sensitive to earthquake-induced groundwater flow, studies of temperature changes after earthquakes can provide useful information on the response of groundwater systems to earthquakes. Clearly more groundwater temperature data are needed to test the present model. Of particular importance will be temperature measurements made at multiple depths and with greater frequency. It will also be helpful to redo pump tests after earthquakes to see if any hydrological

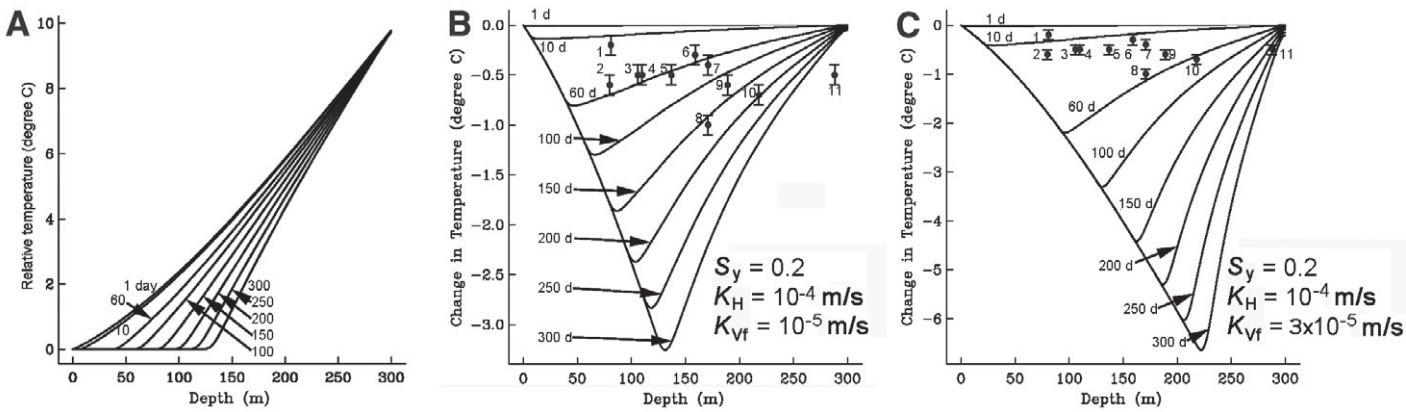

Figure 3. A: Temperature in the fracture zone (relative to the surface temperature) for the reference model. B: Change in temperature for the reference model. Curves are labeled by the number of days after the Chi-Chi earthquake; data points are numbered for the convenience of discussion. C: Change in temperature for a model similar to the reference model except K_{Vf} is increased by a factor of 3.

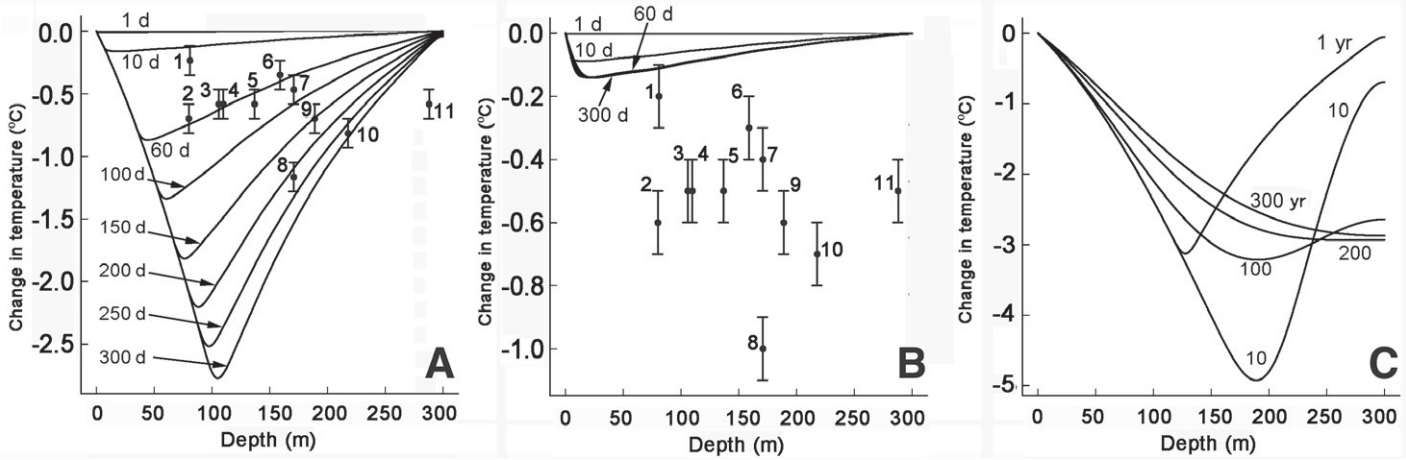

Figure 4. A: Changes in temperature for the "relaxed model" in which K_{Vf} relaxes with time with τ = 2 yr, otherwise similar to the reference model. B: Changes in temperature for a model in which K_{Vf} relaxes with τ = 10 d, otherwise similar to the reference model. C: Change in temperature versus depth from 1 to 300 yr for the relaxed model with τ = 2 yr.

properties did change when temperature changes are documented. Complementary measurements of groundwater composition may also be insightful (e.g., Hartmann, 2006 ; Hartmann and Levy, 2006).

ACKNOWLEDGMENTS

We thank Wen-Fu Chen for providing temperature data, and two anonymous reviewers for helpful comments. Lee-Ping Wang helped the first author in Matlab programming. Manga thanks the NSF for support.

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Manuscript received 20 June 2011
Revised manuscript received 25 August 2011
Manuscript accepted 12 September 2011

Printed in USA