FLUID FLOW DURING TECTONIC DEFORMATION AND CONCOMITANT GENERATION OF THERMAL PRECURSORS TO SEISMIC EVENTS.

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Summary

Experimental evidences have been reported indicating that thermal precursors accompany deformation-induced hydrological perturbations in regions of seismic activity. Characteristic features of such precursory phenomena include relatively slow build up of thermal anomalies followed by rapid return to equilibrium conditions. A convenient model that can account for such features has been developed based on the assumption that flow transients arise as a result of tectonic leakage at fault zones intersecting aquifers. The energy equation relevant in this case has been derived by evaluating enthalpy fluxes associated with lateral and vertical fluid flows as well as that due to volume changes in the permeable layer, generated by deformation-induced alterations in the hydraulic head. Results of numerical simulations indicate that thermal transients arise during the stress build-up period as a consequence of mixing of the infiltrating fluids with those in the aquifer. Steady state conditions are attained within relatively short periods of time due to energy exchange by advection. On the other hand, when deformation ceases infiltration is drastically reduced and consequently return to equilibrium thermal conditions is quite rapid. Thus, under favorable conditions, relatively small changes in deformation pattern can easily lead to abrupt and substantial changes in the local thermal regime. In addition, the size of perturbed zone may have dimensions comparable to those of local geological structures. Comparison of model results with observational records of temperatures in bore holes indicate that the characteristics of thermal precursors depend on a number of factors such as duration of stress build-up, direction of recharge flux, permeability contrast between the confining layer and the aquifer and the local geothermal gradient.

Introduction

Possibility of earthquake prediction depends, in general, on the ability to track down precursory phenomena. Deformation processes occurring in source regions of shallow earthquakes are, in many cases, known to lead to appreciable alterations in subsurface hydrological regimes. The changes are often manifest at the surface in the form of abnormal variations in the levels and discharge rates of subsurface fluids. The basic mechanism responsible for such precursory phenomena is believed to be the time dependant changes in the flow system arising from alterations in the pressure field, hydraulic potential and its gradients. Fluid flows may also arise as a result of relatively rapid changes in the permeability structure of fractures and fault zones, taking place during deformation accompanying seismic activity. Thus, redirection of flows along new paths may occur as a result of changes in the interconnectivity of fracture networks. Similarly displacements along fault planes can either impede or reinforce existing flows or sectorize new flow patterns. Also if deformation processes lead to alterations in pore pressures, then accompanying changes in permeability distribution can be expected. Expulsion of pore fluids are known to lead to collapse of preexisting fracture networks while increases in fluid pressure can lead to enhanced permeability. The net result in all such processes is either short period or permanent alterations in subsurface flow patterns. Attempts have been made in the past to relate observational evidences on changes in subsurface flow systems with patterns of seismicity (Sibson et al, 1975; Yamabe and Hamza, 1996). It is clear that an understanding of on-going changes in subsurface flow patterns is important in understanding the nature of deformation processes.

Direct experimental evaluation of tectonic fluid flows is a difficult task because of the experimental difficulties involved in measurements, under field conditions, of relatively low velocities of groundwater flows (generally less than 10^{-5} m/s). On the other hand, fluid flow is a relatively very efficient means of thermal energy transport in subsurface environments and hence it is reasonable to expect significant temperature perturbations along the flow path. However, because of the rapid thermal exchange with fluids within the flow path the time scales of decay of such perturbations are likely to be comparable to the times for attenuation of flow transients. Thus properly designed thermal monitoring systems are necessary to detect the presence of such transient thermal anomalies. In the present work the characteristic features of thermal anomalies associated with tectonic fluid flows are examined in the light of observational evidences gathered to date as well as through the use of simple models of thermal perturbations.

Model of Tectonic Leakage

Consider the case of a confined aquifer bounded by an active fault plane that is allowing episodic leakage of fluids in response to local tectonic deformation. A schematic diagram of the geometry considered is shown in figure (1). A consequence of such 'tectonic leakage' is rapid lowering of the local piezometric surface, giving rise thereby to infiltration of fluids through the confining layers. In the presence of thermal gradients in the confining layer such recharge will lead to influx of fluids with temperatures different from that of the aquifer. As a result thermal perturbations are generated within the aquifer, coincident with the episode of tectonic leakage. If the deformation precedes earthquake activity such perturbations in the aquifer will appear as thermal precursors.

In developing a model of such thermal precursory activity it is necessary to make simplifying assumptions as to hydraulic properties of the medium, geometry of the flow system and the nature of thermal energy exchange. To begin with, the recharge of the aquifer is assumed to be vertical, taking place through the confining layers. In addition it is assumed that the flow within the aquifer is linear and that the leakage rate is constant, determined by the build-up of tectonic deformation. The fault movements associated with rupture processes are in general discontinuous and of short duration and hence the episodes of tectonic leakage would take place on time scales comparable to those for diffusion of pressure pulses. The periods of such episodic processes are relatively short, and thus it is reasonable to assume that thermal energy exchange take place dominantly by mixing and advection.

Designating the change in piezometric surface as ‘η’, the enthalpy flux associated with the recharge flow is:

$E_r = C_f.\Delta T.(K_1.H_1) = C_f.\Delta T \quad A_1. \quad \eta$ (1)

where C_f is the thermal capacity of the fluids, ΔT the temperature contrast between the aquifer and the confining layer, $A_c = K_c / T_c$, K_c being the permeability of the confining layer with thickness T_c. For a specific value of ΔT the enthalpy flux is directly proportional to the hydraulic gradient H_c. The piezometric surface ‘η’ is thus the ‘head’ that drives the enthalpy flux and has the value ‘η_0’ at the fault plane intersecting the surface. The corresponding mass flux is $M_r = A_c\ \eta$. Thus the total energy flux (kinetic and thermal) is:

$$E_{tr} = A_c.\ \eta.(1 + \rho.C_P.\Delta T) \tag{3}$$

Obviously, if the recharge is isothermal, then equation (3) simplifies to the common case for Darcy flow of isothermal fluids. The continuity equation for non-steady flow in the aquifer can be obtained by considering mass flux components associated with lateral flow, recharge rate and volume change. The relation for mass balance can be written as:

$$(q + \frac{\partial q}{\partial X} dX)\, dt + r\, dX\ dt = q\, dt + \frac{\partial v}{\partial t} dX\ dt \tag{4}$$

where q is the discharge, ‘r’ the infiltration rate, X the distance and t the time. Consider now the enthalpy flux associated with the tectonic leakage from the aquifer. The relevant energy equation can be written down by considering the overall energy balance, that also take into account effects of energy flux arising from compaction due to reduction in pore volume. Under such conditions it is fairly straightforward to show that the enthalpy flux is given by:

$$S\, E_d \frac{\partial^2 \eta}{\partial X^2} - M\, E_C \frac{\partial \eta}{\partial t} = Ac\, E_r\, \eta \tag{5}$$

where S is the storage coefficient and M a dimensionless constant representing the volume change due to pore pressure variations. E_d, E_c and E_r are the components of enthalpy fluxes associated with the tectonic leakage, compaction and recharge processes respectively. Equation (5) is identical to the one for non-steady mass flow in confined aquifers. Introducing the dimensionless variables:

$$y = \frac{\eta}{\eta_0},\ x = \sqrt{\frac{A_c\, E_r}{S\, E_d}}\, X \quad and \quad \tau = \frac{A_c\, E_r}{M\, E_c} t \tag{6}$$

equation (5) can be rewritten as:

$$\frac{\partial^2 y}{\partial x^2} - \frac{\partial y}{\partial \tau} = y \tag{6}$$

Equation (6) can be made homogeneous by a suitable substitution and the solution obtained the Laplace transform method (see for example Carslaw and Jaeger, 1959; Dahl, 1981). As convenient boundary conditions it can be assumed that the leakage rate is constant at the fault plane (∂η/∂x is a unit function) and that the recharge is insignificant at large distances (η → 0 as x → ∝). If, in addition, the initial condition is taken as η = 0 at t = 0, the solution for enthalpy flux associated with local discharge can be given as:

$$E(x,t) = (E_0 / 2) \left\{ e^{-x}\, erfc[m] + e^{x}\, erfc[n] \right\} \tag{8}$$

where

$$E_0 = \eta_0 \sqrt{S\, A_c\ (E_i / E_d)},\ m = \frac{x}{2\sqrt{\tau}} - \sqrt{\tau}\ \ and\ \ n = \frac{x}{2\sqrt{\tau}} + \sqrt{\tau}$$

In deriving (8) it has been assumed that the tectonic leakage rate is constant. For variable leakage rates the solution can be obtained by the method of superposition:

$$E(x,t) = \frac{1}{2} \Sigma E_n \left\{ \beta(x, \tau - \tau_{n-1}) - \beta(x, \tau - \tau_n) \right\} \tag{9}$$

where τ_{n-1}-τ_n represent the dimensionless time intervals during which the enthaly flux had magnitude E_n and β is the function within brackets of equation (8).

A number of numerical simulations were carried out to investigate to examine the influence of model parameters (duration of flow episode, distance from fault zone and permeability of confining layers) on the temperature variation predicted by equation (9). The results indicate that the model is capable of reproducing the characteristic features of thermal precursors. As an illustrative case model results for temperature changes at various distances from the fault zone are presented in figure (2), for the case in which the flow episode has duration of 0.5 days. As expected, the magnitude of the thermal signal decreases with distance from the fault zone but the duration of perturbation is larger at greater distances. Also the magnitudes of perturbation remain significant at large distances, which mean that it is not necessary to have borehole-monitoring facilities installed in localities close to active faults. Figure (3) illustrate the effects of duration of flow at a specific distance from the fault zone. It is clear that the overall time for attenuation of thermal transients has a positive correlation with duration of flow. However, the most conspicuous feature discernible in model results is the rapidity with which perturbations decay after cessation of flow episode. This is a direct consequence of the assumption that fluid mixing is relatively rapid and that conduction does not play any significant role in heat transfer.

Comparison of Model Results with Observational Data

Comparison of model curves with experimental data can be used as a convenient means of obtaining complementary information on the basic parameters that control tectonic leakage. In the present case, records of high-resolution temperature measurements carried out by Buntebarth (1997) at Firjusa (Turkmenistan) were selected for testing model results. One of the records revealed the occurrence of thermal transients at depths of 100 and 150 meters in a borehole in this locality. Buntebarth (1997) considered these transients as precursory signals of an earthquake of magnitude 4.1 that occurred nearly 21 days later at an epicentral distance of 60 kilometers. In both records there are indications that the growth of thermal perturbation takes place during an initial brief period that is then followed by a rapid return to equilibrium conditions. As an illustrative case of model fits consider the precursory signal recorded at a depth of 150 meters. It has features similar to those observed in results of numerical simulations. A set of theoretical curves based on equation (9) were generated for a variety of values of such parameters as duration of flow, distance from fault zone and hydraulic properties of the confining layer and the aquifer. The theoretical curves that bracket the observational data are presented in figure (4). The overall fit of model curves in this case may be considered as reasonably good.

Discussion and Conclusions

In the present work attention has been focussed on analysis of characteristic features of tectonic fluid flows in the light of observational data and discussion of simple models suitable for investigating their thermal effects. Hamza (1997, 1998) pointed out that the nature of thermal signals associated with induced fluid flows are quite different during the various stages of tectonic deformation, with co-seismic signals having larger magnitudes than those occurring during regional deformation preceding seismic activity. Thus it seems reasonable to conclude that seismo-thermal studies have the potential for making significant contributions to understanding the nature of deformation processes in seismically active areas. Foremost among these is the ability to detect hydrologically disturbed zones within areas of seismic activity. Identification of such zones is likely to be of considerable importance in studies of seismic risk.

It is also important to keep in mind the practical limitations of seismo-thermal investigations. One of the prerequisites for implementing such studies is the availability of deep boreholes or wells. This is a serious constraint as suitably located boreholes may not be available in areas of seismic activity. Even in cases where drilling is economically feasible, detailed geological and geophysical surveys may often be necessary for selection of suitable sites. Another complicating factor is the presence of in-hole fluid flows between fracture zones or formations in uncased sections of the borehole, induced by the borehole itself. Such flows can 'smear' out the presence thermal anomalies in boreholes making thereby its experimental detection difficult or practically impossible. Installation of casing pipes can minimize the problem but it is an expensive operation, generally carried out only for shallow sections of boreholes.

Availability of suitable experimental data is another obstacle in quantitative assessment of tectonic fluid flow effects. Even in cases where suitable boreholes are available few attempts have been made to monitor systematically temperature fields over periods of time comparable to recurrence periods of local earthquake activity. Practical difficulties involved in the design, installation and operation of high precision temperature sensing devices having adequate stability in subsurface environments has also been a major obstacle. Geothermal logging equipment can easily be adapted for monitoring subsurface thermal fields over short periods but new technological innovations are necessary if precision measurements are to be extended over time periods comparable with the recurrence periods of earthquake activity. Data acquired in connection with heat flow measurements and assessment of geothermal energy resources have limited use in evaluation of post-seismic perturbations as they provide only an instantaneous picture of the subsurface thermal regime. In most cases presence of transient components in conventional temperature logs are not readily obvious, and in the absence of complementary geological and geophysical information its identification may easily turn out to be a difficult task. This basic limitation of existing geothermal data sets is not often recognized with the result that many of the observed anomalies, in the absence of clear indications of temperature inversions, are traditionally interpreted as arising from steady state heat transfer processes at depth. A reexamination of the available geothermal data would be of considerable help in planning detailed experiments aimed at elucidating the nature of thermal signatures of tectonic fluid flows.

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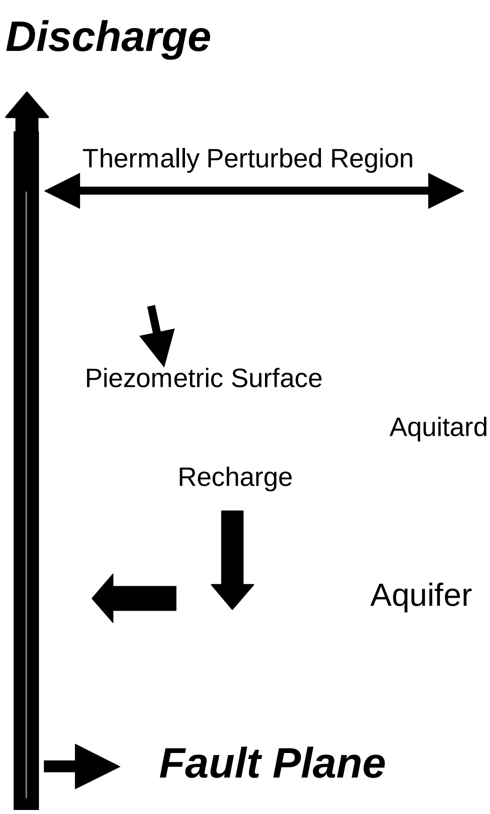

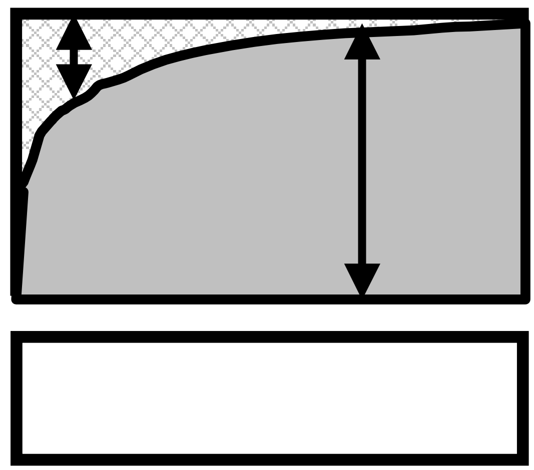

Fig. 1. Schematic diagram of the case in which tectonic leakage of fluids occur in response to local deformation. The permeability distribution is such that the fault zone allows lateral flow of fluids from the aquifer (the bottom blank layer) while the flow is vertical within the confining layer (shaded gray). In the region adjacent to the fault zone the piezometric surface changes in response to vertical flow (stipled area within the gray region).

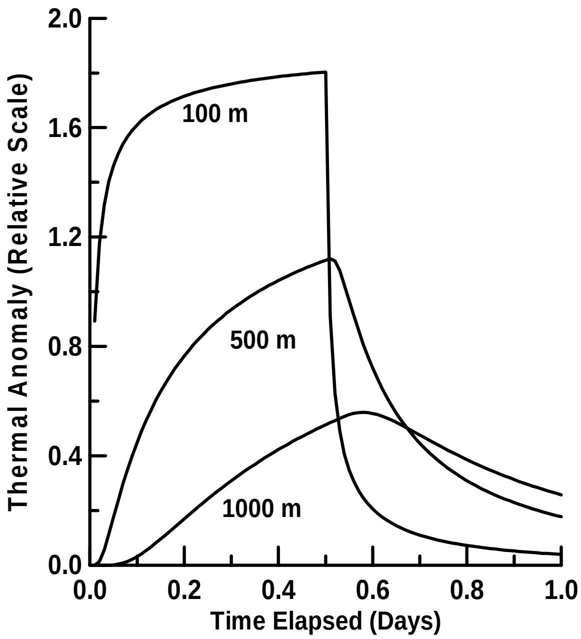

Fig. 2. Model results illustrating growth and decay of thermal perturbations for the case in which the duration of the flow episode is 0.5 days. The numbers on the curves are distance (in meters) from the fault zone.

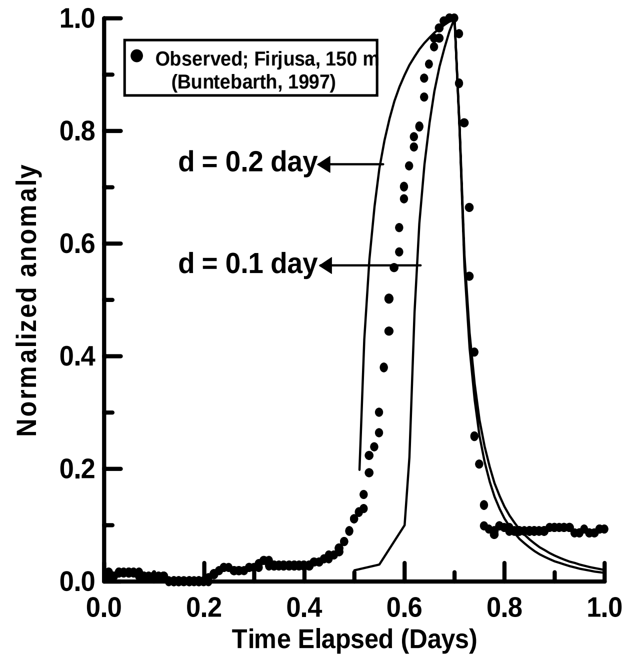

Fig. 4. Examples of the fit of model results (continuous curves) with observational records of anomalous temperature variations (black dots) at a depth of 150 meters in a borehole at Firjusa, Turkmenistan. The numbers on the curves refer to duration of flow episode (in days).

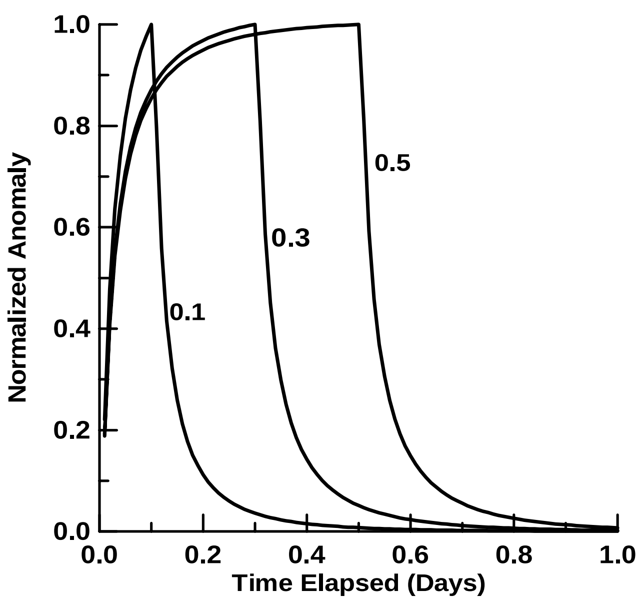

Fig. 3. Model results illustrating growth and decay of thermal perturbations at a distance of 100 meters from the fault zone. The numbers on the the curves indicate duration of flow episodes (in days).