Permeability enhancement in the shallow crust as a cause of earthquake-induced hydrological changes

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CHANGES in hydrology, usually involving increases in stream and spring flow, occur in response to large earthquakes. These changes have been attributed to two very different mechanisms: the expulsion of water from the upper or middle crust due to elastic compression[1], or near-surface permeability enhancements[2–4]. If the former mechanism is correct, then sampling streams and springs affected by earthquakes may provide information about the nature of fluids at depth. Alternatively, if the changes in hydrology reflect only shallow processes, then the behaviour of these fluids provides insight into the rheological response of the shallow crust to earthquakes. Studies following the 17 October 1989 Loma Prieta earthquake in California provided a wealth of information regarding changes in stream and spring flow, groundwater flow and stream chemistry in the region around the earthquake epicentre[1-4]. Here we show that both the initial hydrological response and the hydrology of the region several years after the earthquake are more readily explained by earthquake-induced enhancements of permeability in the shallow crust that are persistent and widespread.

In response to the earthquake, three major changes were observed in the region around the earthquake epicentre: (1) stream flow increased rapidly (generally within 15 minutes after the earthquake); (2) the ionic concentration of stream water increased, but the ionic composition remained essentially constant; and (3) the water table dropped within weeks to months after the earthquake[1-4]. It has been argued that the distribution of stream flow increases induced by the earthquake is consistent with spatial variations in coseismic strain[1] (Fig. 1). Examination of stream flow data near the rupture zone for streams that are not significantly altered by human activity indicates no such correspondence[5]. Although most streams that exhibit flow increases lie in a region of coseismic compression, there is no indication that regions of extension underwent stream flow decreases or showed no change in stream flow. The magnitudes of the increases, even in the region of compression, are independent of the magnitude of coseismic deformation.

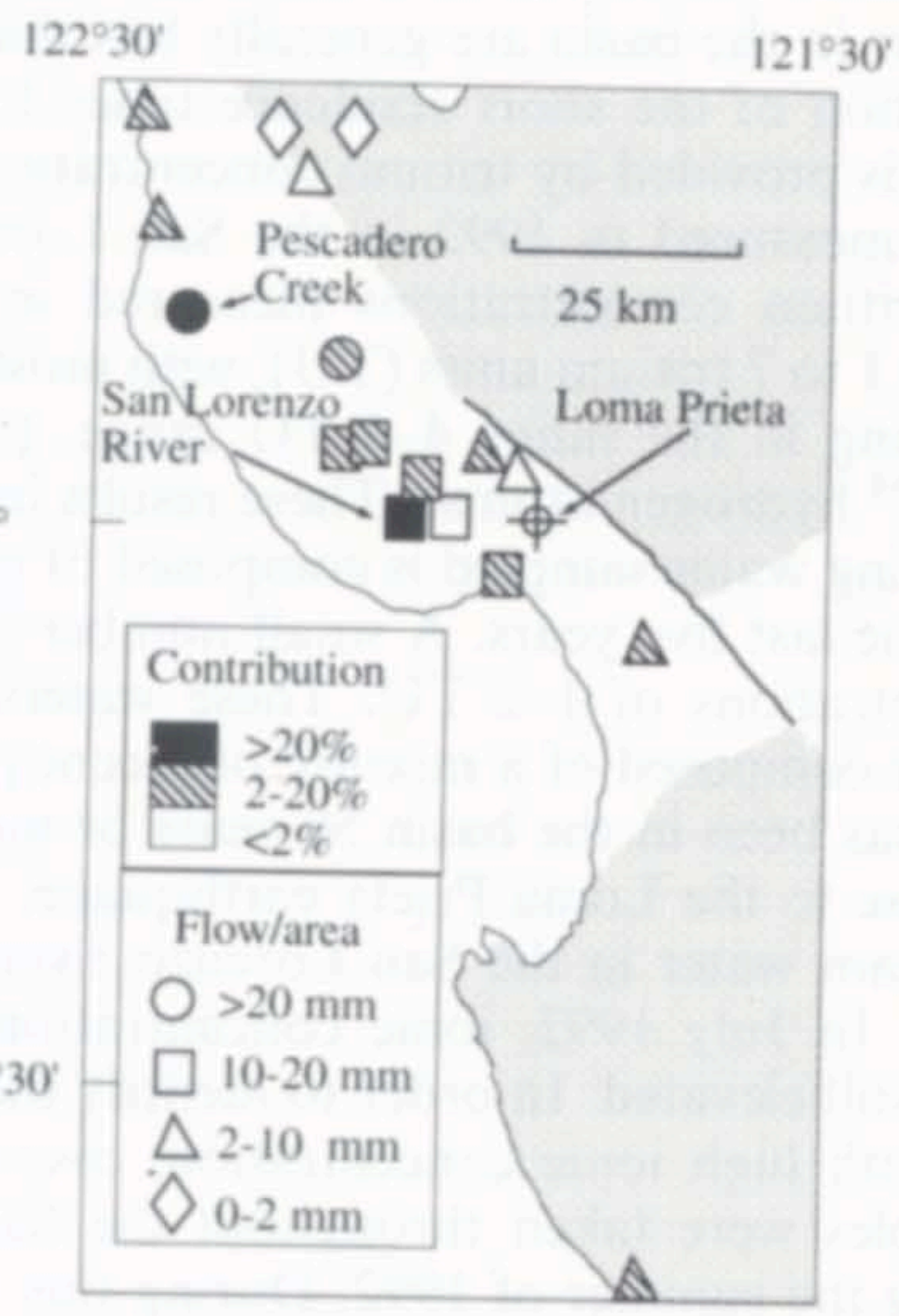

FIG. 1 Location of gauging stations near the Loma Prieta rupture zone monitored at the time of the earthquake. Only gauging stations where flow is not significantly affected by human activity are shown. Shape of each station indicates total volume of excess flow produced by the earthquake divided by the area of drainage. Shading of each station indicates the percentage of the total regional excess flow contributed by each drainage area. The extent of the rupture zone is shown as a heavy solid line. Shaded areas represent regions of coseismic extension at a depth of 2.5 km; unshaded areas represent regions of coseismic compression[1]. Stream flow data are from the US Geological Survey[5] and B. Kraeger (Linsley, Kraeger Associates), personal communication.

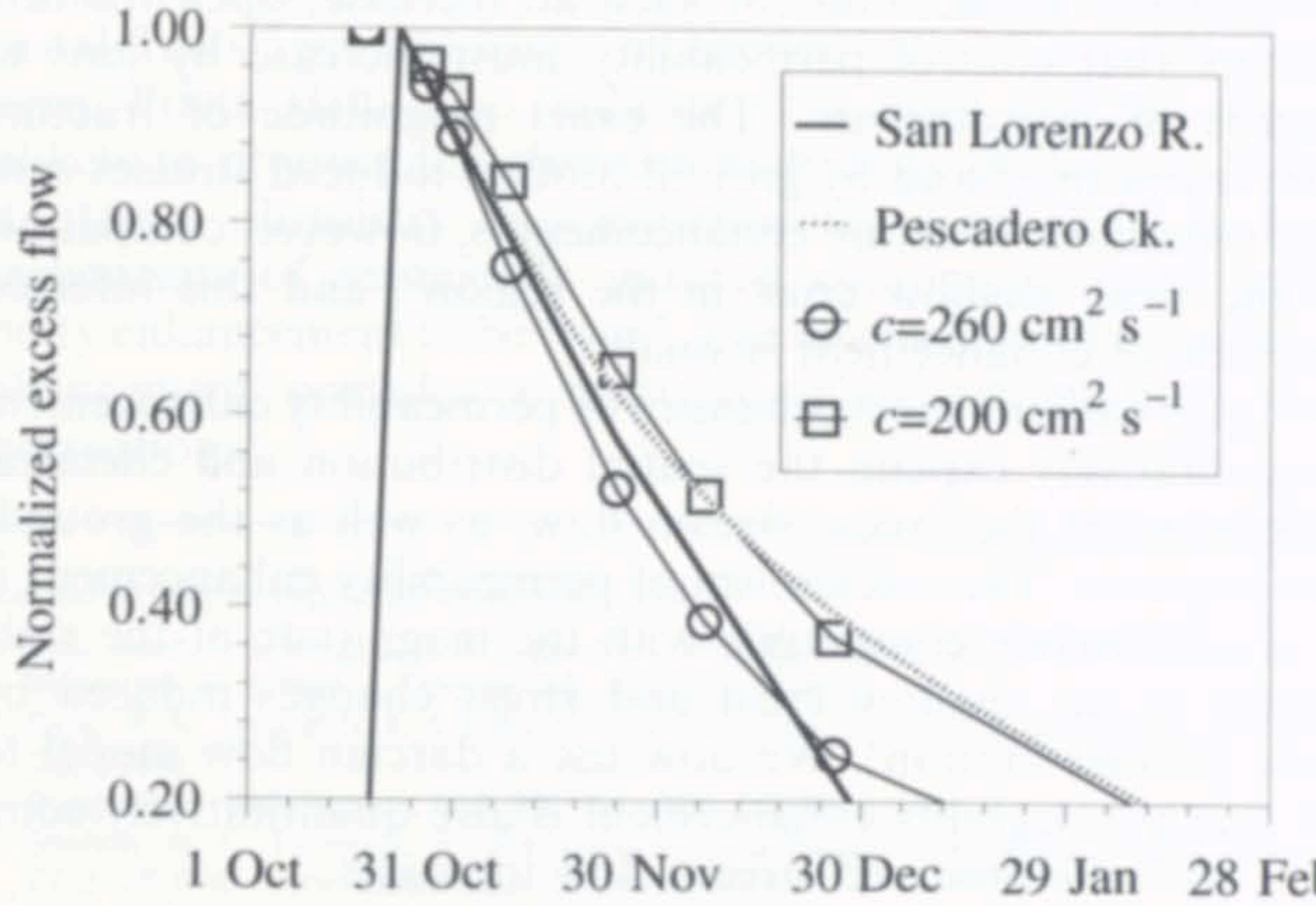

FIG. 2 Comparison of excess stream flow in the San Lorenzo river (thick solid line) and in Pescadero creek (dashed line), with darcian model (circles and squares). Flow at each station is normalized by dividing by the peak excess flow, which is 920 l s^{-1} for the San Lorenzo river and 690 l s^{-1} for Pescadero creek. The model curves show the solution of equations (1–3) in terms of the groundwater flux, v, into the stream as a function of time, t, for two values of the hydraulic diffusivity, c.

$$v=[4k\rho gw/\mu L]\sum_{n=0}^{\infty}[(-1)^n/(2n+1)]\exp[-(2n+1)^2\pi^2ct/(4L^2)]$$

where k is the permeability, ρ is the fluid density, g is the acceleration due to gravity and μ is the fluid viscosity. Although the response of several additional catchments can be described by this simple model, there are also streams that require a heterogeneous darcian model to account for stream-flow response. The ratio of base flow to surface area of the basin suggests that the average permeability of the basin before the earthquake was 10 millidarcies.

The stream chemistry data associated with the earthquake-induced stream flows also appear to be incompatible with elastic-stress-induced crack closure as a viable mechanism. For crack closure to account for the stream flow increases, fluids must be expelled from depths of several kilometres. The lack of compositional changes in stream chemistry precludes a deep source for the excess stream water.

Finally, the observation of water-table lowering in locations that were over 15 km distant from the rupture zone and where stream flow increases were observed[2,6] conflicts with stress-induced compression as a mechanism. Permeability enhancement can, however, explain both augmented stream flow and a dropping water table in the region. An increase in permeability would increase the rate of groundwater flow into the streams. The enhancement of groundwater flow in the absence of enhanced recharge to the groundwater system would create a water mass imbalance and force the water table to drop.

Base flow generally increased by one order of magnitude within days of the earthquake, suggesting that permeability enhancement in the basin increased (on average) by one order of magnitude. To account for such an increase, open fracture diameters that control permeability must increase by tens to hundreds of micrometres[7]. The exact magnitude of fracture enhancement produced by ground-motion-induced stresses cannot be estimated. Fracture enhancement is, however, compatible with the weak shallow crust in the region[6], and this inferred magnitude of enhancement is small.

As noted earlier[2], the mechanism of permeability enhancement can qualitatively explain the spatial distribution and chemical composition of the excess stream flow, as well as the groundwater response. The mechanism of permeability enhancement is also quantitatively compatible with the magnitude of the state of stress in the shallow crust and stress changes induced by seismic ground motion[6]. We now use a darcian flow model to show that permeability enhancement is also quantitatively compatible with the observed stream flow increases.

To examine the theoretical response of stream flow and groundwater levels to permeability changes, we employ a very simple diffusional model of groundwater flow induced by permeability enhancement beneath a hillside. Assuming that the earthquake increases permeability by one order of magnitude, the gradient of the water table will decline and the groundwater flow rate into the stream will initially increase by one order of magnitude. The governing equations and boundary conditions for this model are:

$$\partial^2 h/\partial x^2 = c^{-1}\partial h/\partial t$$
$$h(x, 0) = w((L - \text{abs}(x))/L) \qquad (1)$$
$$h(L, t) = h(-L, t) = 0$$

where h is the hydraulic head, x is the horizontal distance, c is the hydraulic diffusivity, t is time, w is the maximum height of the water table relative to the stream, and L is the maximum length of the groundwater flow path.

Pescadero Creek and the San Lorenzo River accounted for ~65% of the 1.1×10^7 m^3 excess flow produced by the earthquake

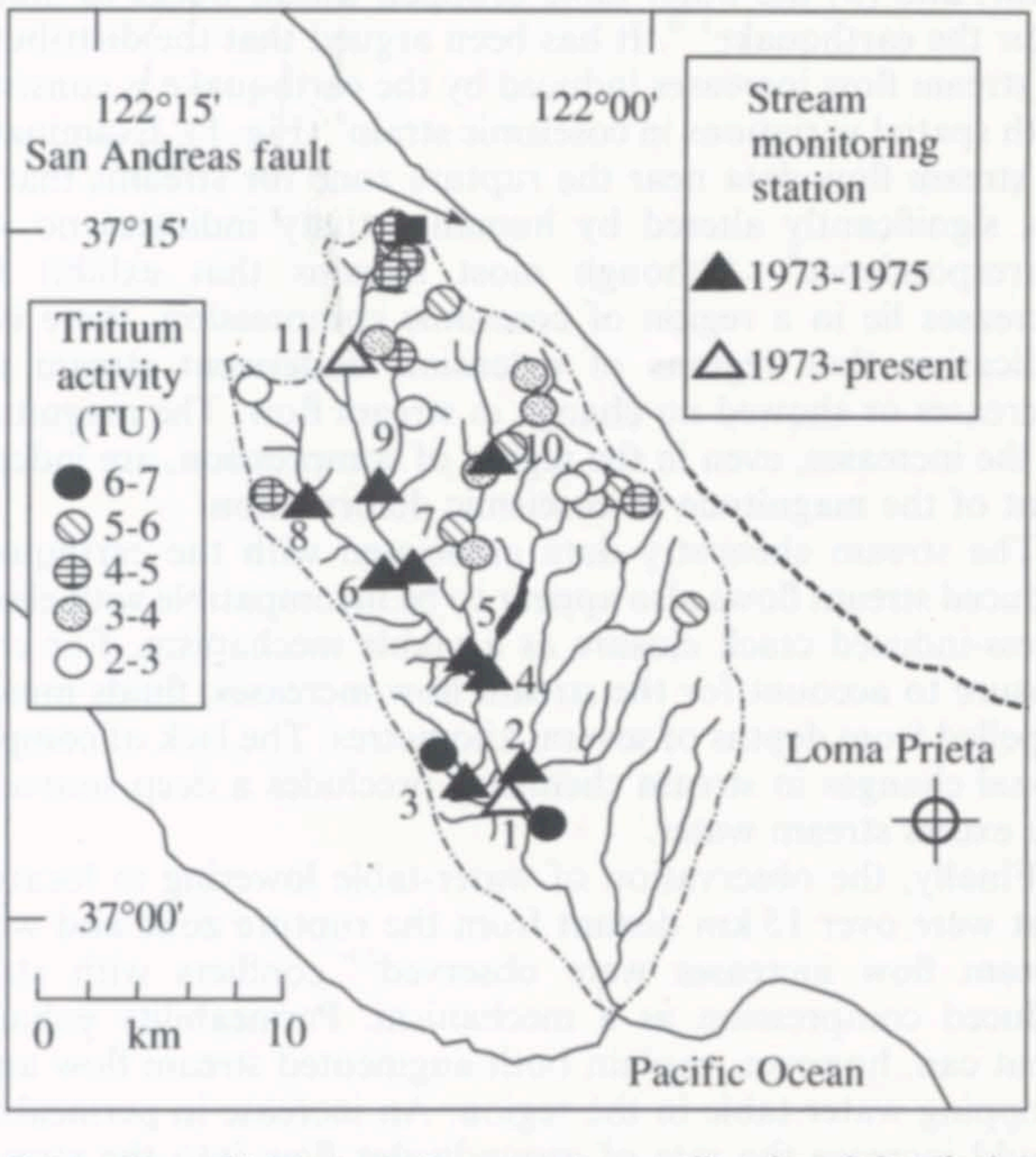

FIG. 3 Location of historical stream water-quality sites (triangles) and tritium collection points (springs and wells) in the San Lorenzo river basin. The river produced ~35% of all excess stream flow in the region. Square denotes location of well tritium samples and pump tests. Tritium concentrations in the precipitation of central coastal California increased from 2 to 3 tritium units (TU) in the pre-bomb period to >500 TU in 1963, and are presently[11] 3–6 TU.

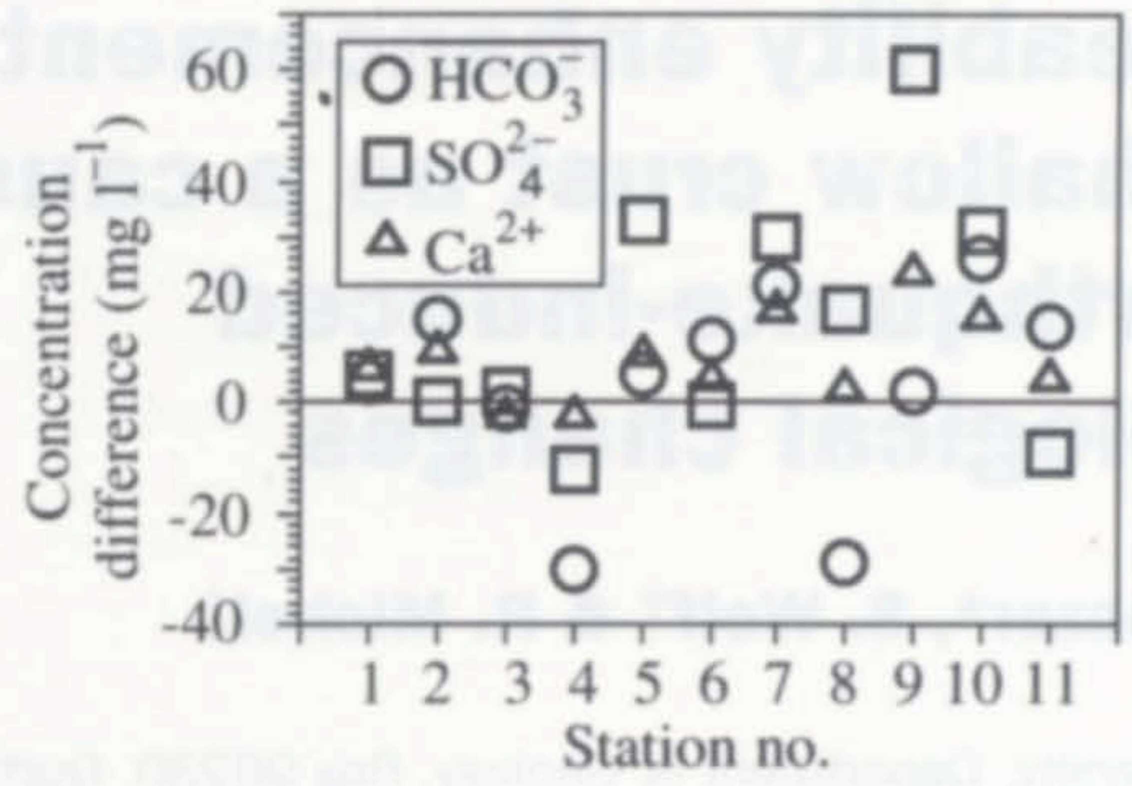

FIG. 4 Difference between dissolved concentrations of HCO_3^-, SO_4^{2-} and Ca^{2+} in 1992 and the highest historical levels at each station. Location for each station is shown in Fig. 3. Urbanization of the region has been slow since the early 1970s; twice-yearly data at one location taken since that time preclude the possibility that the elevated ionic concentrations are due to human influence.

(Fig. 1) and the fit of the model to the excess-flow time series in these basins is shown in Fig. 2. The fits are based on a value for the hydraulic diffusivity, c, of 200–260 cm^2 s^{-1}, and a value for L of 500 m. The model predicts an eventual water-table lowering of 50 m at a distance of 500 m from the stream. Whereas almost all measured and inferred water-table lowering is less than this amount, tens of metres of water-table lowering can be inferred in some regions[2].

If permeability enhancement is responsible for the observed hydrological changes, how long does it last? Reconnaissance hydrology performed in the summers of 1992 and 1993 indicates that the permeability changes are persistent. We hydraulically tested wells at the northern tip of the San Lorenzo river basin that had been found to have undergone significant drops in water-table elevation in response to the earthquake (Fig. 3)[2]. The hydraulic conductivity is generally $(2–5) \times 10^{-4}$ cm s^{-1}. The specific yield (drainable porosity) is generally in the range 0.10–0.15, indicating that the pump tests sampled the hydraulic conductivity of the matrix. The high values for hydraulic conductivity suggest that even if fractures are ignored, residence times for ground water in the basin are generally less than ten years.

Confirmation of the short residence times for ground water in the basin is provided by tritium concentrations of spring and well waters measured in 1992 in the San Lorenzo river basin (Fig. 3). Tritium concentrations measured in the study area ranged from 1 to 7 tritium units (TU), with most tritium concentrations falling in the range 4–6 TU range. (1 TU = 1 tritium atom per 10^{18} hydrogen atoms.) These results indicate that most well and spring water sampled is composed of precipitation that fell within the last five years. A small number of water samples have concentrations of 1–2 TU. These waters are either ~40 years old, or composed of a mixture of recent precipitation and water that has been in the basin 50 years or more.

In response to the Loma Prieta earthquake, ionic concentrations of stream water in the San Lorenzo river basin increased markedly[2,3]. In July 1992, ionic concentrations of the stream water were still elevated. In order to identify the source areas of the water with high ionic concentration, over 100 stream and spring samples were taken throughout the San Lorenzo river basin during the summer of 1992. During this time, storm flow contributions to the streams were minor and the chemical composition of the streams was dominated by the influx of ground water. The short residence time indicates that much of the stream water sampled in 1992 was derived from meteoric recharge that occurred after the Loma Prieta earthquake. At 11 locations, we have historical data on stream water quality taken over the period 1973–75 (Fig. 3)[8]. Comparison of water quality in 1992 with the highest dissolved ion levels recorded in the historical data indicated that ionic concentrations in the northeast portion of the basin were higher than pre-earthquake levels (Fig. 4).

The length of time that the concentrations of dissolved ions have been elevated is consistent with permeability enhancement as a mechanism to explain the hydrological response to the earthquake. Shales in the region have probably undergone long-term permeability changes. The increase in ionic concentration may be attributed to shale units transporting a significantly greater fraction of ground water to the streams. The data are also consistent with the relatively short-lived (6-month) nature of the stream flow increases associated with the earthquake[2]; because residence times of ground water in the basin are short, any stream flow augmentation associated with a lowering of the water table can also be expected to be short-lived. Stream chemistry may be dominated by changes in groundwater flow paths, but stream flow is generally governed by the magnitude of recent precipitation.

Hydrological changes associated with other major earthquakes are also compatible with the mechanism of permeability enhancement, but the data sets associated with such earthquakes focus almost entirely on the magnitude of stream flow. Recent work examining stream-flow response to major earthquakes in North America has shown that such processes as dilatant crack closure[9] and expulsion of pressurized middle-crustal fluids[10] are not easily reconciled with observations[1]. The Loma Prieta data also indicate that such mechansims are unlikely to produce the observed hydrological changes. Finally, the stream chemistry and groundwater data allow both the mechanisms of seismically induced compression and permeability enhancement to be tested. The mechanism of permeability enhancement provides a more complete explanation of the observations. □

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