tration, a completely suitable explanation for the observed coincidences cannot now be advanced. But the correspondence certainly suggests a relationship, possibly unique, of helium depletion and subsequent earthquakes within a large area encompassing the San Andreas and related fault systems.

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ANOMALOUS FLUORINE VARIATIONS IN GROUNDWATER AS EARTHQUAKE PRECURSORS

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Strong earthquakes in China are often accompanied and preceded by geochemical as well as geophysical changes. We report here a study on the variation of fluorine ion (F-) concentration in groundwater and possible relation to earthquakes.

Anomalous F- variations were observed before the magnitude 7.4 Haicheng earthquake of 1975 and the magnitude 7.8 Tangshan earthquake of 1976 at several wells in Tianjin City and Baodi County, and before the magnitude 7.9 Sungpan-Pinwu earthquake of 1976 at several wells in Lanzhow City and Wenxian County. A negative F- anomaly was observed at a well in Beijing before the magnitude 6.5 Ninghe earthquake of 1977.

Significant F- changes were also observed at the times of two explosions of 10^3 ton TNT. The time delay of the changes was found to be proportional to the distance between points of detonation and observation; and the amplitude, inversely proportional.

Rock and water samples were collected from observation wells in the explosion area for model study in the laboratory. Higher F- content of water was observed for rock specimens of smaller grain size and when the specimens were under greater load.

Thus we tentatively conclude that F- content of groundwater may change in response to changing regional stress field and that, under favorable conditions, F- anomalies may be used as earthquake precursors.

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FLUID-PHASE EARTHQUAKE PRECURSOR STUDIES IN SOUTHERN CALIFORNIA

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A monitoring network of 16 thermal wells and springs along the Elsinore, San Jacinto, and San Andreas faults, has been in operation for six years. Temperature, conductivity, radon, helium, and dissolved N_2, Ar, and CH_4 are measured at monthly intervals. Other measurements at less frequent intervals include total CO_2, carbon, hydrogen, oxygen, and nitrogen isotope ratios, Ra-226 and Pb-210 activities, and $^3He/^4He$ ratios. We have established a two-component mixing model for dissolved gases in which compositional variations in thermal springs reflect mixing of an ascending deep component with a "surface" component within the spring. Rn and He variations due to these effects, and to cavitation loss in two-phase systems, are normalized by use of N_2 and Ar variations. Helium isotope ratios show proportions of "mantle" to "crustal" helium throughout the network, and Rn to Pb-210 activity ratios (~ 10^3 to 10^5) show effects of lead scavenging and local radon addition.

Large changes in Rn and He in Arrowhead Hot Springs occurred in May, 1979, 60 ± 15 days prior to the Big Bear earthquake swarm (M = 4.8) in the San Bernadino mountains. Rn and He increased 72%, CH_4, Ar, and N_2 increased by 60%, 25%, and 17%. All concentrations returned to baseline by late 1979. This appears to be a definite precursory event, in which the "deep" component increased relative to the surface component and gas concentrations were less diluted by downward convective mixing. No dilatancy effects were involved. At Frink Spring in the Salton Sea area, He has increased 5% per year since early 1976, with no increase of other components; no reason is yet known.

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THE WIENER "PREDICTION ERROR FILTERING" OF SHORTLINE DEFORMATION DATA BEFORE AND AFTER TANGSHAN EARTHQUAKE

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At Dahuichang Observatory, near Beijing, PRC, short line leveling, water-tube tilt and quartz-tube extensometer data have been used to monitor the crustal deformation over the Pabaoshan fault. The observations started in 1969 and data have been accumulating since then.

The data show yearly large excursions that are clearly related to rainfall and temperature and these excursions mask to various extent the signals that are present in them. Before the Tangshan earthquake (about 180km from the observatory) in 1975, there were obvious changes that cannot be explained by the changes in ambient conditions. Due to disturbances created by rainfall and temperature the time of initiation or the amplitude of such changes cannot be determined.

Wiener predictive filtering has been used to predict the output (i.e., the level, the tilt or the extension) from the input (i.e., the rainfall and temperature). The differences between the predicted output and the actual output, the "prediction errors", are the signal we are seeking.

It can be seen from the prediction errors that an anomaly started to appear in early 1975, more than a year before the July 29, 1976 earthquake. A shorter term anomaly appeared about four months before the earthquake. The total amplitude of the anomalous tilt amounted to about 2mm in 26m. After the earthquake, the leveling and water tube tilt data seem to settle down to a new base values different from those prior to the earthquake.

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WATER LEVEL AND GEOCHEMICAL ANOMALIES AT LAKE JOCASSEE, SOUTH CAROLINA

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Together with induced seismicity at Lake Jocassee, water level has been monitored in a 100 m deep observation well for about 1 year. The observed water level was corrected for recharge from Lake Keowee and barometric pressure changes. The corrected water level exhibited possible precursory changes of 5-12 cm associated with 8 out of 35 events ($1.0 < M_L \leq 2.3$). The anomaly threshold (~5 cm) was found to depend on the magnitude of the event and its hypocentral distance from the well.

Two larger events with $M \geq 2.0$ on April 30, 1980 and one on May 4, 1980 occurred at a distance of about 2 km from an observation spring. There was an anomalous increase in both the seismicity and in the radon concentration of water in this spring. No precursory change was observed in the conductivity or chlorinity of this spring water. However, one day after the April 30 earthquakes there was a further 20% increase in Rn and a day after the May 4 event, there was a large (70%) increase in the chlorinity. No corresponding change was observed in the conductivity. These data suggest that the post-earthquake changes may be associated with a pressure front emanating from the hypocenter and passing through the spring a day later.

S 79

INTERPRETATION OF A HYDRAULIC-FRACTURE EXPERIMENT, MONTICELLO, SOUTH CAROLINA

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Flow-rate and pressure transient data collected during a hydraulic fracturing experiment in a well in Monticello, South Carolina, by the U.S. Geological Survey has been analyzed using a numerical method. The experiment was designed to estimate the in-situ horizontal stress at approximately 300 m depth in granite. The experiment involved three periods of injection with variable flow rates separated by shut-in and bleed-off periods. The generalized numerical model used for interpretation assumes a radially growing, vertical, penny-shaped fracture with finite stiffness and with permeability dependent on aperture. Fracture deformation is taken to be one-dimensional, in the direction of least principal stress. Fracture propagation is controlled by the availability of adequate excess potential energy in the fluid to overcome rock toughness and create new fracture surface. The following system coefficients were estimated by parameter adjustment: initial fracture aperture, fracture stiffness, rock fracture toughness, matrix permeability and well compliance. The best-fit parameters were estimated by matching the entire history of the experiment. Although one cannot obviously claim the estimated set of parameters to be unique, the values used were quite credible in relation to known field and laboratory experience. In particular, the minimum principal stress was estimated to be 0.78 times the lithostatic stress, agreeing well with Zoback's independent estimate of 0.8. A sensitivity analysis showed that the simulations are quite sensitive to rock toughness, leakage into reservoir, in-situ tectonic stresses and fracture stiffness. The success of the present study shows that the proposed approach will facilitate the refined data interpretation required by the increased availability of high precision and high speed measuring devices.

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EARTHQUAKES AND THE DEEP EARTH GAS

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Earthquakes are caused by the sudden fracture of a rock due to a high level of shear stress, and the rapid slippage along the crack so formed. Well-documented precursory effects include an unusual rate of radon emission from the ground, changes in electrical conductivity, ground water levels, seismic velocity; also unusual animal behavior. Major earthquakes have often included eruptions of large amounts of combustible gases.

We believe that high pressure gas originates from deep sources below, and migrates upwards periodically. On reaching shallower levels it distends pore spaces and weakens the rock. Existing stress may now lead to fracture. Without the gas shear stress could not result in violent slippage under the pressure of an overburden of more than 10 km; with the gas present any forming crack can be held open and sudden sliding can occur, causing the earthquake. Slight leakage to the surface prior to the quake is responsible for the various precursory effects noted, and massive release during the quake for eruptions and sometimes flames. Large volumetric changes as are sometimes observed, and also required to account for some tsunamis, can also be ascribed to this. The composition of the gases is regionally variable, but H_2O, CH_4, CO_2 and H_2 are major components.

The direct monitoring of ground gas pressure variations would then be the primary observation, and also the most sensitive, while the other precursory effects would be secondary.

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ATTENUATION OF PEAK ACCELERATION IN THE NEAR-SOURCE REGION OF EARTHQUAKES

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