

# Isotope constraints on the involvement of fluids in the San Andreas Fault System, California

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Fluids are suspected to play a major role in earthquake mechanics, especially in the case of the weak San Andreas Fault (SAF). Models developed to explain the weakness of the fault are similar but rely on different fluid sources. A recent study of groundwaters associated with the SAF has provided evidence for a geopressed mantle fluid source (Kennedy *et al.*, 1997). We present here an isotope study comparing deformation zones (gouges, breccias, fault veins, slickensides, cataclasites), and vein fillings with their hosts and the fluids associated with these materials, as sampled by fluid inclusions. We are investigating *c.* 250 samples from over 20 localities along the San Andreas and adjacent faults from South San Francisco to East Los Angeles (Fig. 1). Samples from the exhumed San Gabriel Fault, a deeper equivalent of the SAF, are included as well as samples from the Santa Ynez Fault, another former strand of the SAF embedded in Miocene limestones. All the major lithologies (granites, gneisses, sandstones, limestones, marbles and serpentinites) have been sampled for isotope analyses of C, O, H, He, Ne, Ar, Sr, Nd, and Pb.

## Carbon- and Oxygen Isotope systematics

Calcite fills most of the veins and repetitively occurs as an accessory mineral in deformation zones. Measurement of  $^{13}\text{C}$  and  $^{18}\text{O}$  depletions in carbonates, especially by comparing deformation zones or veins with host rocks at various scales, may be interpreted in terms of fluid infiltrations (e.g. Pili *et al.*, 1997b). The C- and O-isotope systematics of carbonates from veins, deformation zones and their hosts are presented in Fig. 2. They form a large and consistent trend suggesting percolation by fluids of similar compositions and same origin.

In each sample site, from most to least isotopically

depleted, thus from most to least infiltrated, are the deformation zones, the vein fillings and the host rocks, respectively. Veins cross-cutting deformation zones are even more isotopically evolved (Fig. 2). With increasing distance from what can be structurally defined as the core of fault zones, host rocks are less isotopically affected and the density of veins and deformation zones decreases. The veins abundantly show crack-seal features but most of them are not injected more than once in contrast to the deformation zones. Host-rock carbonates display progressive evolution toward low C- and O-isotope compositions for limestones, marbles, gneisses, granites and basalts respectively, matching the more pronounced metamorphic/ deep crustal origin of their carbonates. Decreasing C- and O-isotope compositions for material from the Santa Ynez, San Andreas, and San Gabriel faults are consistent with otherwise

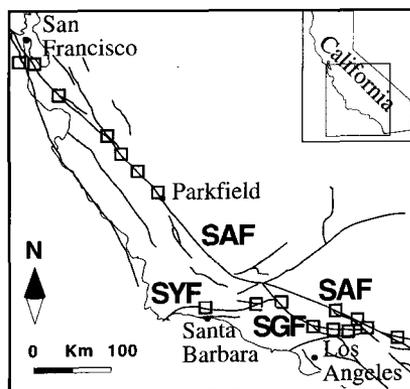


FIG. 1. The San Andreas Fault System and sample site distribution. SAF, SYF, and SGF: San Andreas, Santa Ynez and San Gabriel faults.

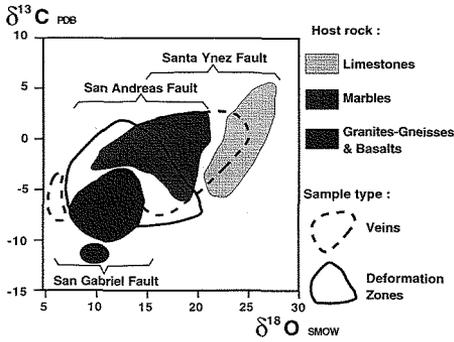


FIG. 2. Carbon- and oxygen-isotope compositions of carbonates from gouges, cataclastites, fault veins, slickensides (altogether called deformation zones), veins and host rocks from the Santa Ynez, San Andreas, and San Gabriel faults.

known progressive deeper levels of faulting from uppermost, upper, and middle crust, respectively.

The maximum isotope depletion of the deformation zones and veins compared to their hosts is larger for oxygen ( $\sim 20$  permil) than for carbon ( $\sim 8$  permil). The fluids are not in equilibrium with the host rocks, at least for oxygen and probably also for carbon, although this is difficult to assert due to the range of compositions spanned by inorganic and organic carbon sources. The carbon isotope depletion is not correlated with the highly variable organic carbon contents and most of the carbonate veins show isotope compositions similar to those of the marbles, or lower.

We infer from the above relations that the fault zones are infiltrated during deformation by fluids of deeper origin dominated by crustal water  $\pm$   $\text{CO}_2$ . Meteoric water does not represent a significant contribution.  $\text{CO}_2$  is inferred to have a metamorphic or mantle origin.

Oxygen-isotope compositions of quartz from gouges, veins, or quartzites associated with carbonates exhibit equilibrium temperatures in the range 150–400°C compatible with faulting at increasing depths in the Santa Ynez, San Andreas, and San Gabriel faults, respectively.

### Noble gas isotope systematics

The isotopic compositions of noble gases from fluid inclusions further constrain fluid origins. Cracked fluid inclusions exhibit helium isotope ratios in the range 0.1–2.5 Ra (Ra is the  $^3\text{He}/^4\text{He}$  ratio in air) and indicate that past fluids percolating through the SAF system contain mantle helium contributions of  $\sim 1$  to

$\sim 32\%$ , similar to that measured in present-day groundwaters associated with the fault (Kennedy *et al.*, 1997). Mantle-derived rocks intruded in the crust are unlikely to be responsible for these helium contributions. The present study of rocks sampled along the traces of the San Andreas Fault system confirms the involvement of mantle fluids and shows from structural relationships observed in the field and in thin sections that these fluids are directly associated with the process of faulting.

### Radiogenic isotopes

We are analysing the isotope compositions of Sr, Nd and Pb from deformation zones, veins, and their hosts to further constrain fluid origins and fluid/rock ratios.

### Earthquake mechanical model

The infiltrated deformation zones, veins and host rocks show that fault zones in the San Andreas system maintain a higher permeability than adjacent regions. Our stable isotope systematics and noble gas measurements both show consistent evidence for the involvement of mantle-derived fluids in faulting, in addition to the infiltration of deep crustal/ metamorphic water  $\pm$   $\text{CO}_2$ . This supports the assumption of a deep source of fluids at lithostatic pressure percolating through and weakening the fault zone (Rice, 1992). Some or all of the  $\text{CO}_2$  may be of deep crustal origin. Although mantle helium will be accompanied by other fluid phases, particularly  $\text{CO}_2$ , combining the mantle  $^3\text{He}$  flux through the fault system with a reasonable mantle  $\text{CO}_2/{}^3\text{He}$  ratio (Kennedy *et al.*, 1997) implies that additional  $\text{CO}_2$  sources are needed to re-establish fault-weakening fluid pressures on a time scale relevant to earthquake cycles.

Mantle-roots and lithospheric fluid flow appear to be common features of giant strike-slip systems, as also shown by Pili *et al.* (1997a and b).

### References

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