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# IMPLICATIONS OF ZEOLITES AND THEIR ZONATION IN THE CAJON PASS DEEP DRILLHOLE

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*Abstract.* Zeolites occur in all cores and most cuttings samples of plutonic and gneissic rock from the Cajon Pass Deep Drillhole. Laumontite or stilbite replace plagioclase and fill fractures <1 mm to several cms in width. Zeolitic alteration is most intense in faulted and fractured zones. Zeolite species are zoned vertically. Laumontite occurs to a depth of 1885 m, stilbite from 1885 m to 2080 m and laumontite again to at least 2524 m. The transition from stilbite to laumontite at 2080 m fits both extrapolated equilibria and the CPDDH P-T gradient but laumontite occurrences above 1885 m are metastable apparently reflecting rapid uplift. Radioactive accessory minerals from the wall rock surrounded by zeolites in some fractures exhibit red-brown haloes. Halo intensity correlates to mineral radioactivity and may allow dating of mineraliztion. Observation in the CPDDH suggest a potential role for zeolites in determining chemical and physical properties such as pore water composition, seismic velocity, and gravity contrasts in faults of the San Andreas system.

## Introduction

An intriguing discovery in the first leg of the Cajon Pass deep drillhole (CPDDH) is the ubiquitous occurrence of zeolites as: 1) fracture-fillings and 2) localized replacement of rock along fault zones in all of the diverse rock types of the basement (Silver and James, this volume). Zeolites are believed to play an important role in determining fracture permeability, composition of geothermal fluids, and geophysical properties of the rocks at Cajon Pass. Their influence on the constitutive properties of rock in and near the San Andreas fault may be large and in turn affect the seismic behavior of the fault. Zonation of the zeolite mineral assemblages may provide important information about the structural history and uplift in the Cajon Pass area.

## Methods

The distribution, mineralogy, and structural associations of zeolites were studied as part of the comprehensive geologic and geochemical investigations related to the CPDDH. Methods included mapping of fractures and faults in the cores, examination of cuttings, petrographic study of thin-sections, analysis of fracture-filling minerals by X-ray powder diffraction (XRD) methods, and examination of fractures and zeolites in nearby surface exposures. Samples for XRD analysis were gently powdered in an agate mortar and deposited with acetone on glass slides. Diffraction patterns were generated on a Scintag PAD V diffractometer using CuK alpha radiation.

## Observations

Zeolite minerals are present in all the basement cores and in virtually all cuttings samples from the CPDDH. This observation led to the examination of nearby surface exposures. Zeolite mineralization is visible in surface outcrops throughout the Cajon Pass area between the drillhole and the San Andreas fault. Vincent and Ehlig (1987, this volume) confirmed that zeolitic veining and alteration in the area increases in proximity to the San Andreas fault. Zeolites occur as a replacement of plagioclase and as fracture-filling minerals. The color of the zeolite minerals ranges from white or gray to pinkish-orange. Fractures may contain a single color of zeolite or several shades representing several stages of mineralization. Calcite is commonly associated with the zeolites replacing fine-grained light grey comminuted rock in fractures. Bleached zones, several mm wide, typically envelop fractures containing zeolite. These zones contain zeolitized and albitized feldspars and zeolitized micas. Extensive zeolitization is associated with many fault zones encountered in the CPDDH, with aureoles having apparent widths up to 50 m.

Typical individual zeolite-filled fractures are 1 mm or less in width but range up to 3 cm. Recovery of larger zeolite veins in cores may have been hampered by their relative incompetence. Spinning of rock fragments in the core barrel may have destroyed adjacent softer materials and, indeed, the core itself. The core intersects thin seams with steep dips (60°-90°) resulting in long fracture traces (2.25 m in core 17) that nearly parallel core axes. The orientation of zeolite-filled fractures is consistent throughout a core. The steep dips, consistent orientation, and wide distribution of these fractures suggest that they may be correlative with a steep SE-dipping fracture set measured using downhole electrical images (Pezard and Luthi, this volume).

Many zeolite seams are zoned in color and texture parallel to the fracture walls, showing several periods of mineral deposition. Lack of offset along the host fractures and internal zoning indicates multiple periods of dilatation and mineral deposition. Most fractures are sealed and core segments coherent when removed from the core barrel. Within several hours of recovery many of the fractures have opened, disrupting the continuity of the core. This behavior may be related to stress relief or to changes in hydration state of the zeolite filling. At all depths there are a few examples of delicate zeolite crystals forming drusy coatings in open fractures. Cross-cutting relations with chlorite-epidote-quartz-filled fractures indicate the zeolite fractures are younger. Several chlorite-filled fractures with apparent dip-slip have later zeolite mineralization deposited in dilatational jogs on their surface.

Several wider (0.3-3 cm) zeolite-filled fractures show evidence of movement. These fractures contain crushed fragments of wall rock entrained in several generations of felted zeolite and calcite. In core 17 laumontite crystals in a 3 cm-wide dip-slip (?) fault zone form radiating rims on rounded and embayed calcite crystals. Laumontite lathes range up to 0.3 mm in length near the edges of the fault but are very fine-grained in the central zones that appear to have accommodated the most, or most recent (?), strain. A fault in core 33 with 2.5 cm of reverse separation and a component of left lateral movement contains stilbite which shows similar textures.

In thicker intervals of alteration, the laumontite appears to partially replace the major minerals in the sequence plagioclase > biotite >> alkali feldspar > hornblende > quartz. In plagioclase the replacement pattern is a three-dimensional patchwork giving the feldspar an "exploded" appearance (Figure 1). In biotite, laumontite appears to develop in thin lenticles parallel to cleavage.

## Halos Surrounding Radioactive Accessory Minerals

In the fault zones crushed mineral fragments contained in the zeolite matrix are comprised of the constituents of the wall



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Fig. 1. Replacement of plagioclase feldspar by zeolite.

rocks. These plutonic and metaplutonic rocks range from gabbros to granites (Silver and James, this volume) and the more felsic contain small amounts of the accessory minerals apatite, titanite, zircon and allanite. Where these accessory minerals have been mechanically liberated from the minerals of the wall rock and engulfed in zeolite each grain is surrounded by a rusty-red colored halo (Figure 2). Other fragmented minerals, quartz, plagioclase, alkali-feldspar, biotite, hornblende, magnetite-ilmenite, chlorite, and calcite, are not surrounded by halos. Halos are well developed in laumontite in core 17 and in stilbite in core 33. There are no unusual optical properties associated with the halos; only their color and opacity. They are not pleochroic. The relative intensity or darkness of halos is related to the mineral it surrounds with allanite halos > zircon > titanite > apatite. The halos extend roughly 20 μm out from the mineral grains, a distance approximately equivalent to the range of U and Th series alpha particles in zeolites.

Our investigations have shown the typical relative radioactivitites of these accessory minerals in many rocks are also allanite > zircon > titanite > apatite. Initial isotope dilution mass spectrometric analyses of the radioactive accessory minerals in cores 17 and 33 are consistent with this ranking. We conclude that the halos are a radiation-correlated phenomenon. To our knowledge, this is the first report of radiation-related halos in zeolite group minerals.

## Vertical Zonation of Zeolites

There is an important zonation of zeolite speciation in the CPDDH (Figure 3 and the lithologic column in Figure 3 of Silver and James, this volume). Core 5 contains a few very thin (<0.2 mm) laumontite-filled fractures identified in thin section. In core 6 at 594-587 m petrographic and XRD data indicate the fracture filling zeolite is laumontite. Laumontite XRD patterns were obtained in cores 17 (1351-1357 m), 19 (1652-1658 m), and in 20 (1737-1744 m) with quartz and albite. No analcime was identified. Samples from core 25 (1884-1885 m) contain a mixture of laumontite and stilbite.

Fig. 2. Radiation-related halos around allanite (a) and titanite (t).

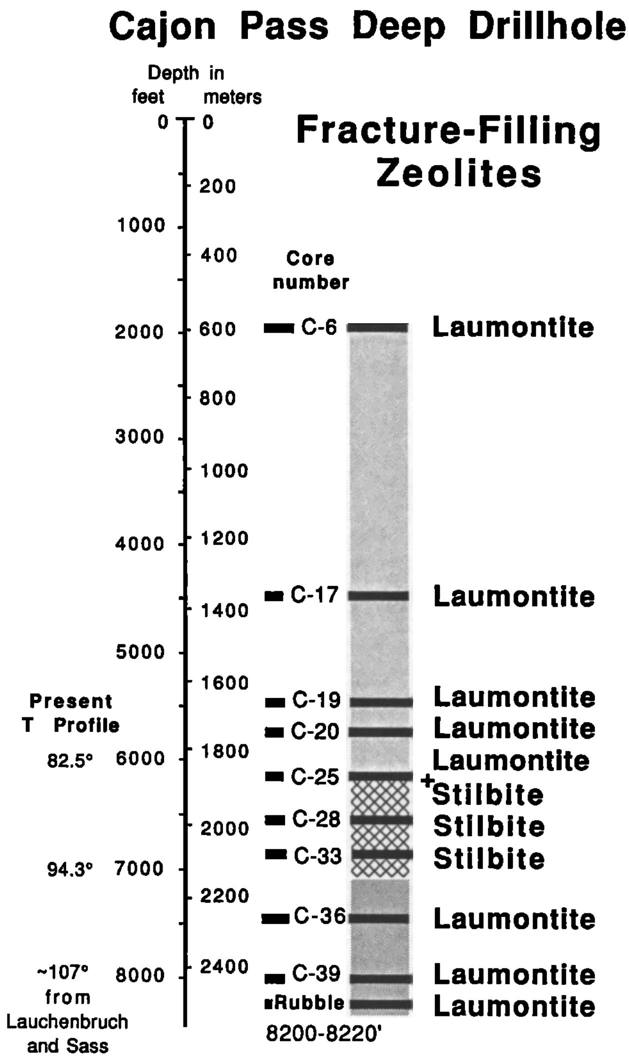


Fig. 3. Zonation of zeolite mineralogy with depth. Temperature profile from Lachenbruch and Sass, this volume.

Cores 28 (1982-1984 m) and 33 (2077-2080 m) contain stilbite. Core 34 contains laumontite and traces of calcite. In preliminary analyses of leg 2 samples, cores 36, 39, and cuttings samples down to 2524 m also contain laumontite and traces of calcite.

## Age of Zeolite Mineralization

The development of zeolites and zeolite-filled fractures in the CPDDH appears to be one of the youngest events in a complicated basement history. Zeolite-filled fractures cut the Cajon Formation (Vincent and Ehlig, 1987), indicating at least some of the mineralization is post-mid-Miocene. All cross cutting relations in the cores indicate that the zeolite-filled fractures are among the youngest natural fractures. Textural evidence indicates there have been several episodes of dilatation and mineralization along the fractures in the hole. The presence of open, crystal-lined fractures at depth suggests that some dilation and zeolite crystal growth may be active.

We are currently investigating whether the halos developed around accessory minerals in laumontite and stilbite may allow more quantitative age estimates to be made for the mineralization. If the development of halos is a simple radiation-induced process without an erasure mechanism their intensity should be a function of the radioactivity of the accessary mineral and the time since the accessory mineral was incorporated in the zeolite matrix. An understanding of the coloration process is necessary to establish a rate constant for its development. We are also exploring the possibility of using uranium series parent-daughter disequilibrium dating of the zeolites themselves.

## Discussion

Observations of extensive zeolite mineralization in both fracture filling and replacement of the rock in the CPDDH and in nearby surface exposures have implications for current processes and conditions near the San Andreas fault, and for various fault-related features in the southern California region.

Our subsurface observations and surface studies by Vincent and Ehlig (1987, this volume) and ourselves suggest that the San Andreas fault is an important locus of zeolitization. This requires further confirmation where local relief and/or drilling in the fault zone can provide three-dimensional information on the extent of the process, its mineralogical zonation and its tectonic controls. Certainly the San Andreas fault is marked by fractured rock of appropriate compositions with abundant geothermal fluids (to >300°C) to permit extensive zeolitization (Wang, 1984; Wang *et al.*, 1986; Irwin and Barnes, 1975). This zeolitic alteration can produce major changes in rock properties by filling fractures, reducing rock density, reducing permeability, altering pore fluid compositions and probably altering elastic and ductile strain characteristics.

In the Cajon Pass drillhole the striking vertical zonation of laumontite from the surface to 1885 m, stilbite from 1885-2100 m and laumontite to 2500 m and deeper is intriguing. If one assumes applicability of the the phase equilibria conditions determined by Liou (1971) and shown in Figure 4, the upper laumontite zone cannot represent processes in that environment. Stilbite is the expected phase based on the extrapolation of his data to low temperatures and pressures. Liou stated that the presence of other solution components (*e.g.* NaCl, $CO_2$ or S) would lower the temperature of the stilbite-laumontite transition. Indeed, deposition of laumontite in surface hot springs rich in Na+, Cl-, $SO_4^{=}$ ions at 43° to 89° has been reported by Barnes, *et al.* (1978) and McCulloh, *et al.* (1981). Whether these are metastable occurrences was not established. These hot spring deposits also contain quartz, potassium feldspar, and gypsum. The CPDDH laumontite fracture fillings contain some rounded and embayed calcite. Cataclastic quartz, potassium feldspar and occasional biotite, hornblende and plagioclase are contributed from the walls of the fracture. Although this assemblage might be compatible with a lower temperature field for laumontite stability, it still appears probable that it formed at some depth below the present surface.

We consider the following model. Meisling and Weldon (in press) and Silver and James (this volume) have described a young active antiform in which the CPDDH basement has been recently uplifted. We propose that rapid uplift of the basement and erosion brought an older, deeper laumontite zone to the near-surface environment where it survives metastably (Figure 4). At the present depth of 1885 m where solutions and adequate temperatures (83°C) provide the activation energy, this fossil laumontite is retrograding to stilbite. At about 2100 m, where Lachenbruch and Sass (this volume) have recorded temperatures of 94°C, laumontite is probably stable and perhaps still actively forming. In support of the somewhat greater age of the upper laumontite zone, one might cite the accumulated radiation-correlated effects in laumontite we report in core 17. The similar halo effects observed in core 33 suggest that this zone has also persisted for an extended period. We infer that the major basement uplift bringing the laumontite to the surface may have begun in the early to mid-Pliocene time when the Cajon Valley and Squaw peak faults were active (Weldon, 1986). More recent arching and unroofing will eventually eliminate the upper zone.

Kharaka *et al.* (1987) reported evidence for more than one composition of pore fluid in the waters sampled from 1830 m to 2115 m. One may speculate that some of the compositional variations may reflect waters equilibrated to the different zeolite assemblages in and near that interval. Further, the capacity of zeolites for selective base exchange may introduce some unusual trace metal anomalies into the fault zones. For example, the uranium series radioactivity anomalies noted on several faults by downhole logs might reflect zeolite ion exchange and selective fractionation. This possibility is under investigation.

The extent of zeolitization at depth seems to be controlled by fractures and faults. The latter are locally accompanied by alteration intervals up to 50 m thick with density reductions up to 10 percent or more (Pezard *et al.*, this volume, Figure 2). Open fractures and/or replacement of ~2.7g/ml rock with

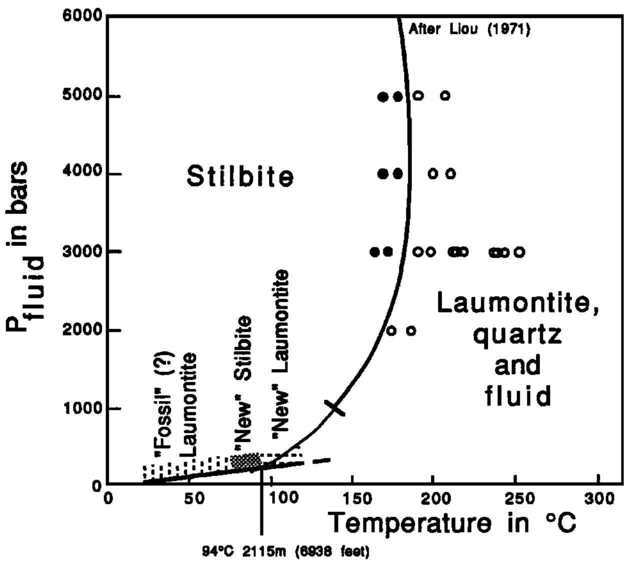


Fig. 4. $P_{fluid}$-T diagram for equilibrium reaction of stilbite and laumontite (Liou, 1971) extrapolated to low P and T. Straight line with patterns indicates Cajon Pass drillhole P-T gradient and ranges of stilbite and laumontite occurrences. Temperature at 2115 m from Lachenbruch and Sass, this volume.

zeolites of density ~2.2-2.3g/ml could account for such anomalies. As noted elsewhere (Silver and James, this volume ) low angle structures appear common in the Cajon Pass geologic column. The intense zeolitic alteration which commonly accompanies the recognized faults may provide these low angle features with reduced densities, modified elastic properties and contrasting seismic velocities, allowing them to serve as efficient seismic reflectors (*viz.*, Leary, *et al.*, this volume)

The role of fault zone rock and mineral composition in the regional seismic behavior of the San Andreas fault has been discussed by several investigators. Allen (1968) proposed a special role for serpentine in localizing fault creep. Wang and his colleagues (1978, 1984, 1986) inferred that the fault properties are consistent with hydrothermally developed clay-rich fault gouge. Sibson (1977) considered that below 5 km, major fault zones may be comprised of cohesive cataclasites altered to zeolite or prehnite-pumpellyite faciès. Very little is known about the physical constants of such altered rocks. The response of zeolites to shearing and crushing, their elastic properties, their temperature and strain thresholds for ductile failure, are pertinent but undocumented.

## Conclusions

This work indicates that zeolite assemblages occur in the Cajon Pass area near the San Andreas fault from the surface to levels at least as deep as 2.5 km. Elsewhere along the San Andreas fault, where the temperature gradient is not anomalously steep, zeolites may occur as deep as 10 km depending on the chemistry and temperature of circulating thermal waters. In the Cajon Pass area zeolitic alteration is found several km laterally from the San Andreas fault. Feng and McEvilly (1983) found low velocities in the fault zone near Parkfield California and notable velocity reversals extending up to 10 km laterally into the Salinian block. Wang *et al.* (1986) employed gravity surveys to confirm the low density character of the fault zone to the bottom of the seismogenic zone in the same area. They inferred 12 percent porosity in fault gouge to explain the effect, a surprising amount considering the depths. A plausible alternative may be zeolitization associated with San Andreas cataclasis and extending to adjacent low angle fault structures in the Salinian basement. Thus selected physical properties measurements on the zeolitized rocks of the Cajon Pass drillhole may provide useful data for modelling the observed geophysical properties of the San Andreas fault at or near seismogenic depths.

Finally, if zeolitization is a pervasive phenomenon at depth along segments of the San Andreas fault, its potential response to critical changes in pore pressure resulting from accumulating strain might be considered a factor in seismic behavior.

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## References

Allen, C.R., The tectonics of seismically active and inactive areas along the San Andreas fault system, Proceedings of the Conference on the Geological Problems of the San Andreas fault system, Dickinson, W.R. and Granz A.R., eds., Stanford Univ. Pub. Geol Sci., 11, 70, 1968.

Barnes, I., Downes, C.J., and Hulston, J.R., Warm Springs, South Island New Zealand, and their potentials to yield laumontite, *Am Jour. Sci., 278*, 1412, 1978.

Feng, R., and McEvilly, T., Interpretation of seismic reflection profiling data for the structure of the San Andreas fault zone, *Bull. Seismol. Soc. Am., 73,* 1701, 1983.

Irwin, W.P., and Barnes, I., Effect of geologic structure and metamorphic fluids on seismic behavior of the San Andreas fault system in central and northern California, *Geology, 3* , 713, 1975.

Kharaka, Y.K., Ambats, F, Evans, W.C., Lamothe, P.J., and White, A.F., Origin of water and solutes in the Cajon Pass well, California,*Trans. AGU, EOS, 68*, 1490, 1987.

Lachenbruch, A.H., and Sass, J.H., The stress heat-flow paradox and thermal results from Cajon Pass, *Geophys. Res. Lett., this volume,* 1988.

Leary, P.C., Henyey, T.L., and Li, Y.-G., Fracture related reflectors in basement rock from vertical seismic profiling in Cajon Pass,*Geophys. Res. Lett., this volume,* 1988.

Liou, J.G., Stilbite-laumontite equilibrium, *Contrib. Min. Pet., 31*, 171, 1971.

McCulloh, T..H., Frizzell, V.A., Stewart, R.J., and Barnes, I., Precipitation of laumontite with quartz, thenardite, and gypsum at Sespe Hot Springs, Western Transverse Ranges, California, *Clays clay min, 29*, 353, 1981.

Meisling, K.E., and Weldon, R.J., Late-Cenozoic tectonics of the northwestern San Bernardino Mountains, Southern California: *Geol. Soc. Am. Bull.*, in press, 1988.

Pezard, P.A., and Luthi, S.M., Borehole electrical images in the basement of the Cajon Pass Scientific Drillhole, California; fracture identification and tectonic implications, *Geophys. Res. Lett., this volume,* 1988.

Pezard, P.A., Anderson, R.N., Luthi, S.M., and Howard, J.J., Structure of the crystalline basement from measurements of electrical resistivity in the Cajon Pass Scientific Drillhole, California, *Geophys. Res. Lett., this volume,* 1988.

Sibson, R.H., Fault rocks and fault mechanisms, *J. Geol. Soc London, 133,* 191, 1977.

Silver, L.T., and James, E.W., Geologic setting and lithologic column of the Cajon Pass Deep Drillhole, *Geophys. Res. Lett., this volume,* 1988.

Vincent, M. and Ehlig, P., Laumontite mineralization in rocks exposed north of the San Andreas fault near the Cajon Pass scientific drill hole, *Geophys. Res. Lett., this volume,* 1988.

Vincent, M. and Ehlig, P., Laumontite mineralization in rocks exposed north of the San Andreas fault at Cajon Pass, California, *EOS Trans. A.G.U., 68,* 1495,1987.

Wang, C.-Y., On the constitution of the San Andreas fault zone in Southern California, *J. Geophys. Res., 89,* 5858, 1984.

Wang, C.-Y., Rui, F., Zengsheng, Y., and Xingjue, S., Gravity anomaly and density structure of the San Andreas fault zone, *Pageoph., 124,* 127, 1986.

Wang, C.-Y., Lin, W., and Wu, F.T, Constitution of the San Andreas fault zone at depth, *Geophys. Res. Lett., 6,* 476, 1978

Weldon, R.J.,The late Cenozoic geology of Cajon Pass; Implications for tectonics and sedimentation along the San Andreas fault: Ph.D. Thesis, Caltech, Pasadena CA, 400 pp. 1986.

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