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GEOHERMAL ALTERATION OF SEDIMENTS IN THE SALTON SEA
SCIENTIFIC DRILL HOLE: PETROPHYSICAL PROPERTIES AND
MASS CHANGES DURING ALTERATION

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SUMMARY OF RESEARCH

The major results of this investigation are as follows:

1) The bulk densities of all lithologies in the scientific drill hole (SDH), but especially the mudstones, increase with depth at a rate that is significantly greater than expected for a normal compaction curve. At depths near 1.5 Km, mudstone bulk densities are 20% above normal for such depths due to the effects of alteration. At greater depths in the SDH and most other wells in the hotter interior parts of the geothermal system, mudstone bulk densities approach grain densities as the porosity approaches zero. There is a strong correlation between temperature gradient and the bulk density of mudstones and the finer grained siltstones. Since these rocks are the dominant lithologies in the geothermal system, the bulk density information should allow the nature of the density anomaly in the geothermal field to be reconstructed using the available regional heat flow information. This in turn should aid the interpretation of gravity and seismic surveys in the area.

2) The normal expectation during alteration and metamorphism is that the grain densities increase as the metamorphic grade increases. In the chlorite to biotite zone sequence in the SDH, the sandstones in general do show an increase in grain density as lower density layer silicate and feldspar minerals are replaced mainly by epidote. For the mudstones, however, grain densities decrease from 2.73 g/cc in the chlorite zone to 2.70 g/cc in the biotite zone as lower density feldspar becomes the dominant alteration phase.

3) As expected from 1), the porosity of mudstone systematically decreases on increasing depth and degree of metamorphism, resulting in porosities in the 1-3% range in the biotite zone. The porosity of siltstones, however, generally increases with depth as the very epidote-rich siltstones of the biotite zone are formed. The process of epidotization results in the replacement of quartz and feldspar by epidote, and extreme solution of quartz and feldspar to form a highly interconnected honeycomb-like pore structure. Thus the porosity of siltstones in the biotite zone is often >15%, and approaches that of sandstone in the chlorite zone. This process may be responsible for considerable deep porosity and fluid holding capacity in the deeper parts of the geothermal system.

4) Mudstones in the chlorite zone that are within 1 meter of sandstone have undergone significant reaction that has produced K-feldspar + chlorite hornfels with higher porosities than normal mudstones at these depths. At the same time, these highly altered mudstones have, in an absolute sense, gained significant K and Fe + Mg, but lost significant Na, Ca, Si, and Al. These changes, which occur over distances of <1 m, in general mirror the overall changes in major elements undergone by all mudstone on increasing depth and temperature through the chlorite and biotite zone, both in the SDH and in the interior wells.

5) Permeability in general follows porosity as expected, with the result that permeabilities over 1 milliDarcy are encountered in deep siltstones of the biotite zone. Because the distribution of porosity is highly variable due to local variations in calcite cement, degree of quartz and feldspar annealing, layer silicate content, and extent of epidote formation, permeability varies extremely on a scale of

millimeters.

6) Incorporation of petrophysical measurements from the interior of the field with those measured in the SDH in this investigation reveals a regular relationship with between permeability and porosity that is identical to that in the Cerro Prieto Geothermal Field. In addition, strong correlations between bulk density and porosity, and bulk density and permeability, should allow a general reconstruction of the distribution of porosity and through-rock permeability in the geothermal system utilizing available geophysical logs. This should provide information on the background porosity and permeability of the reservoir rocks in the system, on which has been superimposed high but localized fracture permeability.

7) The alteration mineralogy observed in the SDH is almost identical to that observed in the interior of the field, and suggests that the drilled section has sampled an alteration temperature range of 220 to 345°C. The SDH most resembles the IID2 and River Ranch 1 wells in terms of the actual alteration minerals in that it contains clinopyroxene, which is not observed in wells further to the southwest in the interior of the field.

8) Detailed comparisons of the changes in mineralogy and major element chemistry for the different rock types indicate that, with few exceptions, open system reactions are dominant during alteration. The result is that, during alteration, a major flux of elements moves between rock and fluid, and from rock to rock by way of the fluid phase. In general, all major elements including Al are mobile in this system. Mudstones in particular lose Al as the Al-rich illite is replaced by less Al-rich biotite and feldspar. At the same time, the adjacent siltstones generally gain in Al as progressively greater amounts of epidote form. Other elemental fluxes are apparent: almost all rocks gain in Fe and Mg in the SDH, but information from wells in the field interior that have reached higher temperatures suggests that the mudstones lose massive amounts of these elements at temperatures above 350°C. where chlorite finally disappears. Thus upward moving fluids might carry Fe and Mg upward to supply alteration reactions in the chlorite and shallow biotite zone.

INTRODUCTION

The availability of core from the Salton Sea Scientific Drill Hole (SDH) has, for the first time, allowed data on various petrophysical properties to be accumulated on geothermally altered rocks at depth in a systematic way. The overall aim of this investigation has been to establish the general variations with depth, degree of alteration, and lithology of such properties as bulk density, porosity, and permeability, through a series of simple, reconnaissance-like measurements of a large number of core samples from the SDH. This will allow the SDH to be used as a model for previously investigated wells in other parts of the geothermal system. This is necessary because: 1) Core is almost completely lacking from the older wells; 2) Most of the older wells have very incomplete suites of geophysical logs; and 3) samples or geophysical logs from the more recently drilled wells in the field interior are not publically available.

The scientific drill hole is located (Figure 1) at the northeastern end of the geothermal system, immediately south of the former CO₂ field. In comparison to wells to the southwest in the field interior (IID2, Elmore and Magmamax wells, etc.), it has a higher percentage of mudstone + siltstone (70%, Herzig et al, 1986), and the siltstones and sandstones are, on average, of a finer grain size. This is entirely consistant with the drilling experience in the well, which has shown the section to be very tight.

The entire investigated section, from 470 to 3020 meters, exhibits a relatively monotonous chlorite and shallow biotite zone alteration, with little evidence of a carbonate caprock with clay-carbonate facies alteration, or of mineralogical or geochemical characteristics of the deeper biotite zone. The dominant alteration assemblage is typical of that found in the 220 to 345°C. temperature interval of the interior wells. The presence of clinopyroxene (Cho et al, 1987) in sandstone at 2484m depth suggests similarities to IID2, where salite-manganiferous ferrohedenbergite occurs throughout the biotite zone (McDowell, 1984; Kramer; 1986, Kramer and McDowell, 1987).

The general textural characteristics of sandstone and siltstone in the SDH are consistant with its flank position in the geothermal field. The quartz and feldspar grains have well preserved detrital morphologies to depths near 1300m. Overgrowths, while present, are in general thinner and less well developed than those observed at similar metamorphic grades in the interior wells. At scattered depths in the 1300 to 2600m interval, overgrowths are extensively developed and low porosity, tight, quartz-cemented sandstones are observed. Relative to the interior wells, however, such silicified zones are less common, and hornfelsic textures become dominant only at depths >2600m, well into the biotite zone. The general impression is of alteration textures in the SDH that are generally less well developed and more erratic relative to the interior wells, suggesting that the SDH remained at high temperatures for a shorter time than many of the interior wells.

This report has been divided into two sections. The first deals with the results of the petrophysical measurements, and the second concentrates on the distribution of alteration minerals and textures, and on a series of calculations of geochemical changes that occurred during alteration.

Figure 1A. Salton Sea Geothermal Field. Summary of temperature distribution (solid lines), surface heat flux (light dashed lines, Lee & Cohen, 1979), magnetic anomaly axis (heavy dashed line, Griscom & Muffler, 1971), gravity high maximum (+, Biehler, 1971), volcanic features (OB = Obsidian Butte, RH = Rock Hill, RI = Red Island, MI = Mullet Island) and geothermal wells (Westmorland Area-DFI = Dearborn Farms 1; L1, L2 = Landers land 2; KFI = Kalin Farms 1; Main Salton Sea Field - S3, S4 = Sinclair 3 and 4; W1 = Woolsey 1; M2, M3 = Magmamax 2,3; E1, E3 = Elmore 1,3; D2 = IID2; SC1 = State California 1; SP1 = Sportsman 1; RI = River Ranch 1; SDH = Scientific Drill Hole; Niland Area - F1, F3 = Fee 1 and 3; B3 = Britz 3).

Figure 1B. Cross section of Salton Sea Geothermal system showing stratigraphic lacustrine mud cap and major alteration zones within fluvial-deltaic section: clay-carbonate facies, chlorite zone, and biotite zone. Isotherms ($^{\circ}\text{C}$) shown by light solid lines. Section runs from Westmorland area to SW through Magmamax/Elmore wells in center of Salton Sea field to Niland area to E.

SECTION ONE: PETROPHYSICAL PROPERTIES

Bulk Density Determination

All bulk density determinations were made by volume displacement techniques in a liquid mercury bath using weighed undercore cylinders or irregular pieces. Previously run standards were used as a periodic check in the measurements. Replicate analyses indicated a measurement uncertainty of less than 1% for pieces over about 5 cubic cm (cc) in volume, and an uncertainty of about 1.5% for pieces near 1 cc. in volume. All bulk density determinations have been summarized in Tables 1, 2, and 3.

Bulk Density Variations

Mudstone Bulk Density

The bulk density of mudstone varies systematically with depth from <2.20 g/cc at depths <700m, through an average of 2.60 ± 0.06 g/cc at 1281m depth (18 measurements in the 1224-1322 m depth range), to an average of 2.69 ± 0.04 g/cc (15 measurements, excluding epidotized mudstones) at all depths >2097m. Since the average grain density at the base of the well is 2.70 ± 0.01 g/cc, these deep mudstones have porosities of approximately 0.5%. The general trend of bulk density with depth through the major data clusters has been illustrated by the shaded band in figure 2, which indicates the variation of the denser and more altered mudstones with depth. At depths <1200m the variation of bulk density with depth is approximately linear: $[(\text{bulk density in g/cc}) = (7.55 \times 10^{-4})(\text{depth in m}) + 1.640]$. The extrapolated 1.64 g/cc surface density is quite reasonable for a water saturated, uncompacted mud with about 40% porosity. The rate of increase of bulk density with depth then falls off very rapidly until, at depths >2000m, the bulk density approaches a constant value of 2.70 g/cc for most mudstone.

Mudstones with bulk densities that fall off the general trend have been delineated by open circles in figure 2. In the well sampled 1224-1322m interval, the two deepest samples at 1321.6 and 1322.0 m have bulk densities near 2.71, contain the first significant epidote (4 and 15 %, respectively), and have porosities in the 2-4% range. These mudstones are located near the shallow limit of the siltstone/sandstone-rich 1356-1570m interval (Preliminary Sp log interpretation) in which epidote contents of 12-30% are encountered in the coarser grained rocks. Mudstones at 1312.3 and 962.4m have bulk densities that lie off the general trend, and both contain unusually high amounts of chlorite (38 and 32%, respectively) and K-feldspar (39 and 67%).

In the poorly sampled 1582-1985m interval, almost all mudstones have bulk densities less than the trend on figure B1. Some of these low bulk densities are due to the fact that the actual samples used are silty mudstones at or near the mudstone/siltstone grain size boundary. This is clearly the case for the two biotite-zone mudstones at 2225.6 and 2226.3m depth. However, the degree of alteration also appears to have an effect on bulk density. Of the 5 mudstones with low values, 4 occur in mudstone-rich depth intervals and contain some calcite cement. The single sample in a sandstone-rich interval is carbonate-free, but the general XRD mineralogy of all these samples is more like mudstones at depths <1200m which have similar low bulk den-

TABLE 1 Mudstone Petrophysical Measurements

Depth meters	Grain Density g/cc	Bulk Density g/cc	Porosity, Vol %	Permeability mD	Sonic Velocity Km/sec
477.3		2.02	(25)		3.15
613.0		2.20	(19)		
749.1		2.27	(16)		
754.8	2.81	2.28	21		3.33
907.5		2.27	(16)		
912.2	2.82	2.38	16		
947.1		2.29	(16)	0.121	4.25
962.4	2.73	2.54	7		
1059.3	2.72	2.38	12		3.80
1064.5	2.73	2.40	12		
1157.3	2.73	2.56	6		
1161.9	2.79	2.48	11		
1163.4	2.72	2.53	7		
1166.1	2.78	2.61	6		
1224.5	2.77	2.61	5		
1225.9	2.81	2.63	6		
1227.9	2.74	2.63	4	0.006	4.99
1230.8		2.56	(6)		
1234.1	2.73	2.59	5		
1235.6	2.74	2.57	6		
1238.8	2.73	2.62	4	0.006	4.99
1297.7		2.59	(5)		
1300.0	2.73	2.61	4		
1308.0	2.68	2.53	8		
1312.3	2.75	2.45	11		
1312.7	2.72	2.61	4	0.000	
1315.9	2.71	2.55	6		
1316.1	2.77	2.60	6		
1318.0	2.71	2.62	3		
1320.1	2.74	2.59	6		
1321.6	2.76	2.71	2		
1322.0	2.82	2.71	4		
1582.0	2.70	2.64	2		
1699.2	2.76	2.45	11		
1837.5	2.69	2.59	4		
1838.8	2.69	2.57	4	0.011	4.96
1840.4	2.72	2.54	7		
1985.3	2.65	2.57	3		
2097.2	3.24	2.69	(1)		
2164.1	2.70	2.72	0		
2165.9	2.70	2.73	0		
2225.6	2.83	2.52	11		
2226.3	2.71	2.55	6		
2300.3	2.70	2.66	2		
2302.3		2.72	(0)		
2349.8		2.73	(0)		
2350.7		2.73	(0)		
2480.4	2.70	2.71	0		
2486.3	2.68	2.71	0		

TABLE 1 (Cont'd)

Depth meters	Grain Density g/cc	Bulk Density g/cc	Porosity ₁ Vol %	Permeability mD	Sonic Velocity Km/sec
2558.9		2.62	(4)	0.000	
2559.5		2.68	(2)		
2682.3	2.70	2.68	1		
2745.5		2.70	(0)		
2819.4		2.67	(2)		
2819.8	2.70	2.70	0		
2884.0		2.69	(1)		

1-Porosity determined from measured bulk density and grain density calculated from XRD analyses except those in () which were estimated from porosity-bulk density equation in text.

TABLE 2 Siltstone Petrophysical Measurements

Depth meters	Grain Density g/cc	Bulk Density g/cc	Porosity, Vol %	Permeability mD	Sonic Velocity Km/sec
605.1	2.72	2.06	24		3.18
608.1	2.73	2.12	22		3.04
748.6	2.70	2.16	20		
749.0	2.70	2.23	18		2.76
915.4		2.41	(11)		
922.1		2.06	(24)		
950.8		2.04	(25)	1.97	3.15
1062.1	2.70	2.35	13		3.59
1064.7	2.70	2.42	10	0.042	3.83
1155.6	2.79	2.49	11		3.74
1157.4	2.69	2.50	7	0.042	4.08
1162.6	2.73	2.46	10	0.017	
1168.1	2.75	2.43	12		3.21
1170.8	2.73	2.43	11		3.81
1222.0	2.93	2.54	13		
1225.4	2.80	2.53	10	0.022	4.09
1293.3	2.69	2.34	13	0.191	4.16
1304.2	2.69	2.41	10	1.53	3.86
1317.9	2.71	2.43	11	0.106	3.80
1415.4	2.80	2.34	17	0.224	4.13
1420.4	2.87	2.48	14		
1427.1	2.68	2.14	20	1.39	
1839.3	2.68	2.50	7	0.046	4.44
1984.2	2.67	2.51	6	0.007	
1984.5	2.82	2.66	18*	3.84	5.09
2060.4	2.77	2.55	8	0.025	4.47
2225.2	3.09	2.38	23*		
2301.3	3.14	2.51	20*		
2483.1	2.85	2.61	21*		
2683.2	2.71	2.61	4*	0.005	
2884.1		2.73	(0)		
2887.8A	3.09	2.78	10*	0.026	
2887.8B	2.96	2.73	8*		
2955.5	2.74	2.71	1*		

1-XRD calculated porosity except for: () = estimated from porosity bulk density equation in text; * = Model calculated porosity .

TABLE 3 Sandstone Petrophysical Measurements

Depth meters	Grain Density g/cc	Bulk Density g/cc	Porosity ₁ Vol %	Permeability mD	Sonic Velocity Km/sec
473.4	2.67	1.79	33	726.	2.50
747.0	2.67	2.26	15*		2.98
940.3A	2.73	2.11	23	1.05	2.61
940.3B	2.67	2.18	18*	29.8	3.25
953.1	2.69	2.18	19*		
955.7	2.68	2.08	23	32.0	2.47
958.0	2.69	2.44	9	0.243	
958.8	2.67	1.92	28*	263.	2.25
961.1	2.67	2.02	24	14.4	2.30
1160.3	2.66	2.19	18	3.52	2.59
1164.2	2.66	2.25	16	2.94	2.72
1305.2	2.71	2.30	15	7.93	3.39
1308.8	2.68	2.41	10	1.07	3.47
1311.2	2.69	2.34	13	0.868	3.16
1419.8	2.88	2.70	6		
1426.1	2.84	2.52	11		
1837.7	2.73	2.63	4		
2618.4	2.69	2.31	14*	5.60	
2618.5	2.69	2.35	13*		
2772.2A			2**		
2772.2B			1**		
2954.8	2.78	2.62	6*		
3020.0	3.12	2.84	9*		

1-XRD calculated porosity except for: () = estimated from porosity-bulk density equation in text; * = Model calculated porosity ;
 ** = Point counted porosity from thin section.

Figure 2. Mudstone Bulk Density (g/cc) variation with Depth (Km). Open circles indicate off-trend values discussed in text. Lines enclose trend of most altered mudstones.

Figure 3. Siltstone Bulk Density (g/cc) variation with Depth (Km). Open circles indicate values discussed in text. Lines enclose envelope of altered mudstones from Figure 2 for comparison

sities and very low-grade chlorite-zone mineral assemblages. Thus some mudstones with low bulk densities at depths >1500m suggest a relative lack of alteration due to lack of fluid access, and may have preserved anomalously low temperature physical properties and mineralogical assemblages. This pattern is entirely consistent with the overall stratigraphy of the well, since the percentage of sandstone and siltstone is highest at depths <1432m, diminishes significantly in the 1432-1930 m interval, and is very low at all greater depths. At the opposite extreme, most mudstones in the well sampled sandstone-rich 1224-1322m interval have XRD mineralogies which indicate significant alteration, and have relatively higher bulk densities as a consequence of that alteration. This in turn suggests that these relatively high bulk densities, at such shallow depths, are directly related to the degree of alteration of the mudstone.

Siltstone Bulk Density

Siltstones show an increase in bulk density with depth, but show far more variation and consistently lower values at a given depth than do mudstones (Figure 3). Thus in the well sampled 1222-1320m interval the siltstone has an average bulk density of 2.45 ± 0.08 g/cc compared to 2.60 g/cc for most mudstones. In general, siltstone bulk densities approach those of mudstone at depth <800m or >2700m. At shallow depths, the convergence of siltstone and mudstone bulk densities reflects both an increase in the argillaceous component of siltstone, and relatively high carbonate cement contents.

There again appears to be a relationship between stratigraphy and bulk density, as there was for mudstone. Thus the very low bulk density siltstones at 922.1 and 950.8m (circles in figure 3) are calcite-free, K-feldspar rich siltstones from a very sandstone-rich interval in which the sandstones and the adjacent mudstones have been extensively feldspathized. Siltstones from adjacent, less sandstone-rich intervals have distinctly higher bulk densities and contain significant amounts of calcite cement. Similarly, the anomalously low bulk density siltstone at 1427.1m is also extensively feldspathized, contains significant hematite and open pore space but no calcite, and is located at the base of a 12m depth interval in which the sandstone has been extensively feldspathized and contains significant epidote. Siltstones from the chlorite zone that are adjacent to major sandstone aquifers, where significant alteration has occurred, have had their calcite cement removed, porosity increased, and are significantly altered, with a resulting overall decrease in bulk density.

The deepest group of siltstones have bulk densities near 2.73 g/cc (figure 3), significantly higher than most other biotite zone siltstones in the 1984-2700m interval. While the epidote contents of both groups of siltstone overlap, the deeper siltstones all contain significant amounts of authigenic biotite or actinolite and distinctly lower porosities, while the shallower biotite zone siltstones are much more porous and contain trace amounts of biotite or actinolite at most. Siltstone is poorly sampled in the biotite zone due to the dominance of mudstone at depths >1800m, but the data does suggest a discontinuity in bulk density and porosity at the point where biotite and actinolite become major authigenic phases.

Sandstone Bulk Density

The limited number of measured sandstone bulk densities indicate a crude increase in bulk density, with a great deal of scatter at any given depth. Those sandstones that approach the mudstone envelope shown in figure 4 have such relatively high bulk densities mainly due to the presence of a high density cement such as calcite (16% calcite at 747.0m), or epidote (22% at 1419.8m, 49% at 3020.0m), or chlorite (37% at 958.0m). Those sandstones with the lowest bulk densities are in general those with no cementing phases, high relative porosities, and a mineralogy dominated by framework quartz and feldspar with or without overgrowths. Thus the sharp contrast between the epidotized sandstone at 3020.0m, with a bulk density of 2.84 and a porosity of 9%, and the very clean sandstones at 2618.4 and 2618.5m which have only 5 % epidote and porosities near 14%.

Overall Bulk Density Changes

The changes of bulk density with depth for all lithologies has been summarized in Figure 5. A clear increase with depth is indicated, with the envelope of most altered mudstones providing an upper limit on the bulk density. In Figure 6, that mudstone envelope has been compared to mudstone/shale bulk densities determined from geophysical logs from both the Salton Sea and Cerro Prieto Geothermal systems, and from other diagenetically altered and buried shales. The two other examples (dashed line R of recent sediments from Nafe and Drake, 1957; and solid line G from Dickenson, 1953) represent "normal" compaction curves for buried mudrocks. The shaded area labelled U in the figure is taken from the data of Seamount, 1982, and represents log-determined bulk densities of mudstones from the montmorillonite zone of the Cerro Prieto Geothermal Field. This zone corresponds to the low temperature clay-carbonate facies of the Salton Sea system, and is found in the shallowest portions of the interior and flank wells, as well as throughout most of the Niland and Westmorland wells. The similarity of the clay-carbonate facies mudstones with the "normal" compaction curves indicates that outside the geothermal systems, the variation of bulk density with depth follows the well established compaction curves of deep sedimentary basins.

The mudstone bulk density-depth envelope of the SDH clearly falls far off these normal compaction curves, and allows the component of bulk density due to alteration, as opposed to compaction, to be determined. The overall effects of alteration are to create a major density anomaly with a density contrast for mudstones of 0.4-0.5 g/cc relative to non-geothermal mudstones outside the geothermal systems. Since mudstones are the major lithology in the system, and siltstones, whose densities approach those of mudstone, are the second most abundant lithology, a significant density contrast of the whole field relative to the surrounding sediments is clearly indicated.

Unfortunately, this density contrast is smeared out over a very large area around the core of the geothermal field. Thus mudstone bulk densities from wells in the Westmorland area (Muromoto and Elders, 1984), as indicated by the field labelled W in the figure, are clearly intermediate between that of the SDH and the "normal" non-geothermal compaction curves. These wells, as well as wells in the Niland area, have shallow temperature gradients of about 85-90°C./Km.,

Figure 4. Sandstone Bulk Density (g/cc) variation with Depth (Km). Lines enclose envelope of altered mudstones from Fig. 2 for comparison.

Figure 5. Bulk Density (g/cc) variation with depth (Km) for all lithologies. Lines enclose envelope of altered mudstones from Figure 2 for comparison.

while most of the non-geothermal areas have temperature gradients near 51°C./Km. (Lachenbruch, 1985). The information in Figure 6 can thus be used to estimate the density-depth relationships for areas of different shallow temperature gradients or heat flows. The regionally available heat flow information can be combined with the information on Figure 6 and used to define the shallow density-depth models for various localities in the Salton Trough.

Finally, area I in Figure 6 represents the log-determined bulk densities of mudstones in the field interior from Muromoto and Elders (198 , Magmamax 2 and 3 wells). These wells, which have higher temperature gradients than the SDH, also have higher mudstone densities at shallow depths. The deeper parts of these interior wells, most of which are less than 1500m in depth, have mudstone densities that converge with those in the SDH, suggesting that the best density-depth curve for the deep interior portions of the geothermal system would be a composite curve of area I plus the SDH envelope at depths $>1200\text{m.}$

Grain Density Determination

All grain densities (Tables 1, 2, and 3) have been calculated either from quantitative XRD analyses (run at U. California Riverside, Williams, personal communication, 1987) of core or from point counts in thin sections of the coarser grained rocks, using mineral densities consistent with the known composition of the mineral phases (McDowell and Elders, 1980 and 1983; McDowell and Paces, 1985; Kramer, 1986; Yau, 1986; and Donaghe, 1987, personal communication).

Grain Density Variation

It is often assumed that, as a result of alteration or metamorphism, the grain density of altered rocks in general increases on increasing temperature due to the dominance of dehydration and decarbonation reactions. Examination of the grain densities calculated in this investigation indicate that, for mudstones at least, the grain density of chlorite zone mudstone is greater than that of mudstone from the biotite zone. As is apparent from figure 7a, shallow ($<1425\text{m}$) chlorite zone grain densities (unshaded in figure) vary from 2.70 to 2.82 g/cc, but the distribution is decidedly assymetric, and the most commonly occurring value is 2.73 g/cc. The high density tail, to the right of the arrow in the figure, consists entirely of mudstones with significantly higher contents of epidote, or chlorite, or illite + chlorite + calcite. In the deeper chlorite zone (1425 - 1985m), the mudstone grain densities are lower, in the 2.68 - 2.73 g/cc range (diagonal shading in figure). The biotite zone mudstone densities are still lower (solid in figure), in the 2.65 - 2.71 g/cc range excluding one highly epidotized sample, and most mudstones have a density of 2.70 g/cc. This grain density decrease is due to the loss of lower temperature, denser illite and calcite, and their replacement by albite and K-Feldspar in the biotite zone.

The grain density distribution of sandstone and siltstone (Figure 7b) is as varied as that of mudstone. In the chlorite zone, most siltstone densities are 2.70 ± 0.03 , while most sandstones densities are 2.68 ± 0.02 . For both lithologies, densities >2.73 occur only in those rocks that have high percentages of layer silicates or epidote. The grain densities of biotite zone siltstone and rare sandstone have

Figure 6. Comparison of Bulk Density (g/cc) variation with Depth (Km) for altered mudstone from SDH (Heavy envelope with tick marks), with mudstones from other areas based on geophysical log interpretations. Shaded area I from interior wells of Salton Sea Geothermal Field, W from wells in Westmorland area (Both from Muramoto and Elders, 1984), U from least altered mudstones from Cerro Prieto Geothermal Field (Seamount, 1982). Solid line G for Gulf of Mexico mudstones (Dickenson, 1953), dashed line R from recent sediments of Nafe and Drake (1957).

Figure 7. Histogram of Grain Densities (g/cc) calculated from XRD or modal data for mudstone (Figure A) or siltstone + sandstone (Figure B). Open areas for shallow chlorite zone mudstone or chlorite zone siltstone, diagonally shaded areas for deep chlorite zone mudstone or chlorite zone sandstone, solid areas for biotite zone samples. Note change of scale in Figure B for high density biotite zone sandstone and siltstone.

an extreme range due to the presence of epidote, from 2.69 to 3.30 g/cc. Epidote contents over 10% produce grain densities over 2.75 g/cc, and since epidote is such a common constituent of biotite zone sandstones and siltstones, the average grain density of these rocks in the biotite zone is distinctly greater than their equivalents in the chlorite zone. Thus the increase in metamorphic grade from chlorite to biotite zone produces a decrease in the grain density of mudstone, but an increase in the density of the coarser grained rocks.

Determination of Porosity

For all mudstones, and most coarser grained rocks, porosities were calculated from bulk densities measured at Michigan Tech by mercury immersion, and grain densities calculated using mineral modes or quantitative XRD analyses. These porosities are referred to below as XRD calculated porosities. With few exceptions, the Riverside and Michigan Tech core samples were taken immediately adjacent to each other from the same lithologic layer.

Where grainsizes were coarse enough to point count reliably in thin section, porosities were measured directly using blue-stained epoxy to highlight the pore spaces (Table 5, in section 2). These point counted porosities were compared to the XRD calculated porosities in part as a check, and in part to provide information on the porosity distribution on the scale of a few cm. As an additional check, and for rocks for which no XRD data exists, mineralogical modes obtained during point counting were also used to calculate a grain density and, using measured bulk densities, a porosity. This porosity is referred to as a modal calculated porosity to distinguish it from the two methods of porosity determination above.

A comparison of porosities determined by the three methods outlined above indicates reasonable agreement in most cases. Where discrepancies occur, they are usually due to the extreme inhomogeneity of the cements in the sandstones and siltstones. Thus, for siltstones at 1984.4m and 2483.1m, the samples taken for quantitative XRD analyses contain significantly less epidote (10-15%) than the thin sectioned samples (68-70%). The sandstone at 961.1m is also a good example. While the average point counted porosity is 18%, the actual porosity ranges from 50% in a small portion of the thin section to a low of 7% due to the very patchy nature of the calcite cement. Since the bulk density was measured on a large piece, the XRD or modal calculated porosities presumably are more representative of a larger volume of rock. In some instances, the point counted porosity severely underestimates the rock porosity, as in the case of the siltstones at 1062.1 and 1064.7m. In both cases the pores are filled with a very fine grained, microscopically unresolvable mixture of calcite and layer silicates which contains significant pore space. The lack of blue epoxy in this particular example is due to the inability of the epoxy to penetrate into the sample during impregnation. As a general rule, however, indications of lack of penetration of epoxy during impregnation were very rare.

The final porosity values have been summarized in Table 1, 2, and 3. In most cases where the porosity was determined by several techniques, the XRD calculated porosities were used in the table if no serious discrepancies between measurements exist. Where no XRD ana-

lyses are available, the modal calculated porosities are used since a larger volume of rock is involved. At 1984.5 and 2483.1m, the modal calculated porosities were used in preference to the XRD calculated porosities because of the extreme variation in epidote content between the thin sections and XRD samples. In most cases, the rocks were sufficiently homogeneous that the adjacent pieces used for XRD at Riverside and bulk density measurements at Michigan Tech gave consistent results. In rare instances, however, sample variability yielded unrealistic results. For instance, in the case of the mudstone at 2097.2m, the pyrite content of the XRD sample is significantly higher than the pyrite content in the core piece used for bulk density determination, so that the XRD calculated porosity is severely overestimated.

Mudstone Porosity

The calculated mudstone porosities show a general decrease with depth (Figure 8), approaching 0% porosity at the base of the well. Using averages over selected depth intervals, the mudstone porosity decreases from 16.3% (10 values) in the 477.3-1064.5m depth range, through 5.6% (22 values) in the well sampled 1157.3-1322.0m interval, and 5.2% (6 values) in the poorly sampled deep chlorite zone, to 1.4% (18 values) in the biotite zone at depths from 2097.2 to 2884.0m.

Much of the scatter in porosity values appears to be related to the type and degree of alteration of the mudstone. In the shallow chlorite zone, mudstones adjacent to sandstone aquifers have been pervasively altered to K-feldspar + chlorite rocks. These extremely altered mudstones (open circles in Figure 8) generally have higher porosities than normal chlorite zone mudstones at a given depth. At depths >1500m, in almost all mudstones the albite content has increased from a normal 14% to 30% or more, while K-feldspar has increased from 6 to >20%, yielding total feldspar contents of over 50%. In the 1500-2500m depth range, those feldspathized mudstones that have 10 to 30% illite/muscovite have porosities of 3% or less and contain 2-12% calcite, while those that are low in or lack mica (open triangles in Figure 8) are calcite free and have much higher porosities. At depths >2500m all mudstones contain >15% biotite and have porosities in the 0-2% range. There is no detectable relationship between chlorite content and porosity.

Siltstone and Sandstone Porosity

The porosity of the coarse grained rocks varies from 1 to 33%, and varies widely over very limited depth ranges. Porosity variations on increasing depth for siltstone (Figure 9) do not show a regular decrease, while for sandstone (Figure 10) a crude decrease is indicated, especially at depths <2000m. Those rocks with >10% calcite (open squares in figures) generally have lower porosities, especially in the case of siltstone. If significant amounts (>20%) of epidote are observed, however (open inverted triangles), significant porosity occurs to the base of the well. Again, this effect is particularly obvious for the better sampled siltstones, where the porosity varies from 8 to 23% for epidotized siltstone in the biotite zone, while other siltstones from this zone have porosities of 8% or less. In the case of sandstone, while the epidotized varieties have

Figure 8. Variation of Porosity (Vol %) with Depth (Km) for mudstone from SDH. Dots for normal mudstone, open circles for those with >40% Ksp + Chl, open triangles for those with >50% total feldspar.

Figure 9. Variation of Porosity (Vol %) with Depth (Km) for siltstone from SDH. Dots for normal siltstone, open squares for those with >10% calcite, filled triangles for those with >20% epidote, X for those with >10% biotite.

Figure 10. Variation of Porosity (Vol %) with Depth (Km) for sandstone from SDH. Dots for normal sandstone, open squares for those with >10% calcite, open triangle for epidotized sandstone, X for those with >10% biotite.

Figure 11. Variation of Porosity (Vol %) with % Epidote (A) or % Calcite (B). Solid circles for sandstone, open circles for siltstone, estimated trend lines in (A) for siltstone (dotted line) or sandstone (dashed line), in (B) for both sandstone and siltstone (dashed line).

Figure 12. Variation of Porosity (Vol %) with Bulk Density (g/cc) for all lithologies. Dots for normal rocks, open circles for epidotized rocks.

porosities of 2 to 9%, the most porous sandstone in the biotite zone is a very clean, open sandstone with only 5% epidote. For both lithologies, the only two samples with significant biotite (>10%) have very low porosities (X in figures 9 and 10).

In investigations of diagenesis in clastic rocks, calcite is, in the simplest view, assumed to be a space filler whose removal is directly related to the creation of secondary porosity. If that is the case, then the percentages of calcite and porosity should be inversely related in a relatively simple way. As is apparent from figure 11a, calcite and porosity from the chlorite zone are inversely related, and the creation of secondary porosity, as long as epidote or biotite are not present, is simply a matter of removing the calcite while leaving the framework minerals relatively intact. The figure also emphasises the differences between sandstone and siltstone. In the chlorite zone, most sandstone has high porosity and is calcite free, while siltstone has more calcite and lower porosity. Sandstones with porosities near 20% and no calcite contrast with siltstones with about 10% calcite and porosities near 11%.

The relationship between epidote and porosity in siltstone is distinctly different (Figure 11b). In general, as epidote increases, the porosity also increases, strongly implying that the epidotization of the clastic rocks is a process that creates porosity at the expense of the framework minerals. This is especially true in the case of siltstone, where porosities of >15% in rocks which contain >50% epidote are encountered. The extreme reaction of the framework grains is apparent in thin section, where quartz and feldspar are both replaced by epidote and dissolved to create pore space. The result is a honeycomb-like texture in the quartz and feldspar with a very complex, extensive, and interconnecting porosity structure. In the most extreme examples, the textures suggest that more than half the available pore space was created at the expense of the framework minerals, rather than simply being unfilled previously existing pore space.

It is also clear from figure 11b that the epidote content of siltstone is significantly greater than that in sandstone. In addition, while the sampling of epidote-rich sandstones is poor, the figure suggests that in sandstone epidote content and porosity are inversely related. This in turn suggests that while the extreme epidotization of siltstone resulted in significant reaction of the framework quartz and feldspars, the formation of epidote in the sandstones was more like a simple pore filling process with relatively little involvement of the framework minerals. The single sandstone with 49% epidote also contains significant actinolite as a felted mass of hairlike, pore filling grains.

The end result is that, at depth in the biotite zone, the epidotized siltstones have porosities significantly higher than most sandstones, suggesting that these rocks are the main reservoir rocks at depth. Since siltstones are far more abundant than sandstones in this well, this is clearly an important source of deep porosity.

Several explanations for the difference in behavior of sandstone and siltstone are possible. The epidotized siltstones in fact could be former sandstones in which the quartz and feldspar grains are so reacted that their grain size has been reduced to the siltstone size range. Alternatively, since in a stratigraphic sense the local progression normal to the sedimentary layering is usually mudstone to siltstone to sandstone, so that most sandstones are surrounded by

siltstone, the extreme epidotization of siltstone may in fact reflect the flux of elements from the mudstone through the siltstone to the sandstone. Most of the extreme epidotization occurs in the siltstones because the elements needed for reaction reach the siltstones first and are consumed there, and because they contain more layer silicates that can act as a local Al-source.

Porosity-Bulk Density Correlation

The relationship between bulk density and porosity is illustrated in Figure 12. With the exception of the epidotized rocks (open circles in figure), almost all lithologies plot on the same general trend which has been fit with the straight line: Porosity (in %) = $96.61 - 35.38 (\text{Bulk density in g/cc})$; ($R=0.98$, epidotized samples excluded). This curve may be used to estimate the porosities of the bulk of the lithologies in the SDH and other parts of the Salton Sea Geothermal System, using bulk densities obtained from geophysical logs and assuming fluid densities of unity. Extrapolation of this curve to the remainder of the geothermal field is justified by the general similarities in measured porosities, alteration mineralogies, and grain densities between the SDH core samples and cuttings and rare core from other geothermal wells in the system. The porosities represent background porosities for most of the altered rocks in the system, and in local instances higher porosities are expected where extremely epidotized siltstones are encountered.

Permeability

Permeability to air measurements were made on 1/2 inch diameter, 1 inch long subcore pieces drilled parallel to the axis of the 1 inch subcores originally obtained from the SDH core. Because these original subcores were drilled perpendicular to the well bore axis, all permeability measurements made are subparallel to bedding surfaces. All measurements were made in duplicate, and corrections were applied for day to day variations in atmospheric pressure. The permeameter was initially calibrated using previously run standards. Groups of core samples were measured over as short a time period as possible to minimize the effects of atmospheric pressure and temperature changes.

Permeability measurements have been summarized in Tables 1 and 2. Despite the large number of undercore samples used in this investigation, it was possible to obtain only a moderate number of reliable permeabilities due to the presence of fractures in many of the samples. In particular, it was exceedingly difficult to drill an intact 1 inch diameter undercore in the deeper parts of the well as it would immediately break into pieces due to the abundance of open fractures in the rock. The measurements that have been obtained are sufficient to give a rough estimate of the between-fracture permeability of the rocks, information of great significance to those interested in mass exchange and mineral reactions within the altered rocks of the geothermal system.

The permeability of siltstone ranges from $<0.01\text{mD}$ (milliDarcies) to a high of 3.8mD . If extremely epidotized siltstones are excluded, a decrease in permeability on increasing depth is apparent (Figure 13). The two siltstones with significant epidote (solid symbols in figure) have permeabilities well above those of more normal siltstone at similar depths. The shallower sample, at 1984.5m depth, is a very clean siltstone with a porosity of 18%, 68% epidote and traces of biotite and chlorite, that shows extreme corrosion of the quartz and feldspar grains. It also has the highest measured siltstone permeability of 3.8mD . The thin section investigations indicate that high porosity siltstones with essentially layer silicate-free pores and epidote contents $>45\%$ persist to depths of at least 2483.1m, suggesting that permeabilities $>1\text{mD}$ might persist to these depths. The deeper epidote-rich siltstone, from 2887.8m, has a much lower permeability of 0.03mD , an epidote content of about 25%, 10% porosity, and, most significantly, about 8% biotite and 5% chlorite.

The contrast between these two samples suggests that if highly epidotized, layer silicate-free siltstones persist throughout the biotite zone, permeabilities $>1\text{mD}$ might be expected in the localized strata where they are found. These high permeability horizons would be surrounded by siltstones with moderate epidote contents, significant layer silicate contents, and much lower permeabilities. The very limited data suggests that these latter rocks become dominant with increasing depth.

It is important to emphasize that permeability varies significantly on a very small scale. For instance, the high permeability, epidotized siltstone at 1984.5m that contains only traces of layer silicates is within 0.05m of a siltstone that, on an x-ray basis, contains over 30% layer silicate and, presumably, a much lower permeability. Interlaminated siltstone and mudstone on a millimeter scale are common, and while one siltstone layer may be epidotized with clean

Figure 13. Variation of permeability ($\text{Log}_{10}K$ in millidarcies) with depth (m) for mudstones and siltstones from the SDH. Solid symbols for epidotized siltstones.

Figure 14. Variation of permeability ($\text{Log}_{10}K$ in millidarcies) with depth (m) for sandstones from the SDH.

abundant pores, the next siltstone may be layer silicate-rich with significantly lower porosity. Even within siltstone units that are relatively homogeneous from a grainsize point of view, the distribution of highly epidotized, porous siltstone ranges from well defined layers to very irregular patches within siltstone with much lower epidote and more normal layer silicate contents.

Sandstone permeabilities range from 0.24 to 726mD., but the available data is not sufficient to establish any trend with depth (Figure 14). The single biotite zone sandstone at 2618.4m depth has a porosity of 14%, very clean, open pores, and only 5% epidote. Most deeper sandstones have significantly lower porosities, and epidote contents near 20%. As noted previously, the epidote in these sandstones acts mainly as a pore-filling cement that reduces porosity and, presumably, permeability. If these samples are representative of the deeper parts of the biotite zone, one would expect much lower permeabilities there than were measured in the chlorite zone. If highly epidotized sandstones exist at depths in the biotite zone, these too may act as local high permeability zones. A sandstone at 3020.0m with 49% epidote and a porosity of 9% may be a potential high permeability sample, although the 13% actinolite, which forms as a pore filling felted aggregate of thin hairlike crystals, would clearly act to reduce permeability.

Despite the limited data, there are several interesting trends present that allow several useful generalizations to be made. In particular there is a strong relationship between permeability and bulk density if the highly epidotized samples are excluded, as indicated in figure 15. Since bulk density may be estimated from geophysical logs, this relationship is clearly of relevance in that it will allow field-wide estimation of the background (ie, non-fracture) permeability of the system as a function of depth and temperature, assuming a fluid phase with a density close to 1 g/cc. Such a density is indicated for the fluid phase of IID2 by Helgeson (1968), and where non-unity densities are suspected, the bulk densities can be adjusted accordingly. Superimposed on this background permeability would be much more localized zones of high permeability through the clean highly epidotized siltstones (and sandstones?), as well as very high permeability open fractures. There is, as expected, a clear lithologic and mineralogic effect on permeability, as indicated in figure 15. For a given bulk density, sandstones have a higher permeability than do siltstones, and for both lithologies, those with high percentages of chlorite + illite and/or calcite have lower permeabilities. In contrast, the highly epidotized siltstones plot far off the trend, and have anomalously high porosities and permeabilities relative to other siltstones.

In order to increase the data set of 35 permeability measurements on SDH core, 19 additional measurements (McDowell, 1981 and unpublished data) on rare core from the interior of the geothermal field, and the Wilson 1 petroleum well, have been added to Figure 16. Again, the contrast between the siltstones and sandstones, as well as the epidotized samples (3 siltstones, 1 sandstone), is apparent. Linear least squares fits through the data indicate, for all lithologies, that $\log_{10}(\text{permeability in mD}) = 13.417 - 5.916(\text{bulk density in g/cc})$, ($R=0.91$); while for sandstones alone, $\log_{10}(\text{permeability in mD}) = 12.703 - 5.289(\text{bulk density in g/cc})$, ($R=0.85$).

There is, in the petroleum industry at the present time, a tendency to downplay permeability measurements made in the laboratory relative to those made in the field, since the lab measurements almost

Figure 15. Variation of permeability ($\text{Log}_{10}K$ in milliDarcies) with Bulk Density (g/cc) for SDH samples. Open circles for sandstones, filled circles for sandstones with high % of chlorite + illite a/o calcite, open triangles for siltstones, filled triangles for siltstones with high % chlorite + illite a/o calcite, E for epidotized siltstones, X for mudstone.

Figure 16. Variation of permeability ($\text{Log}_{10}K$ in milliDarcies) with Bulk Density (g/cc) for SDH (this investigation) and other Salton Sea geothermal wells (McDowell, 1984 and unpublished). Filled circles for sandstones, open triangles for siltstones, E for epidotized sandstones and siltstones. Linear least squares lines shown for all lithologies (solid line) and for sandstones (dashed line). See text for equations.

always yield lower permeability measurements than do well tests. This has led to the suggestion that the laboratory measurements damage the delicate mineral grains and cause clogging of pore throats with the debris, among other things. For this particular set of specimens, most of the sandstone are very clean, and there are few such delicate mineral grains to cause clogging. In addition, formation of detrital grain overgrowths and grain boundary annealing has formed a mechanically strong framework for the porosity that is not likely to be damaged relative to the much less well consolidated, lower temperature sediments of oilfields. As noted in Figure 15, the lowering of permeability by about 1/2 a log unit for the more layer silicate-rich samples may be real, or may be due to damage during measurement as noted above. However, SEM examination of the layer silicates also indicates relatively large, hexagonal books of chlorite in continuous 3-dimensional aggregates that are much better crystallized, coarser, and more interconnected than SEM photographs of chlorite in petroleum field sediments. In my opinion, the measurements of permeability on these geothermally altered sediments represent real, through-rock permeabilities that can be used as background permeabilities relative to high permeability fractures.

The relationship between porosity and permeability for all available measurements from the Salton Sea and Cerro Prieto Geothermal systems is shown in Figure 17. The plotted data includes the 35 measurements from this investigation on the SDH, the 19 measurements on other core from the Salton Sea Geothermal System (McDowell, 1981, and unpublished data), and from the Cerro Prieto Geothermal System, 24 measurements from Seamount (1981) and 9 from Lyons and van de Kamp (1980). The Salton Sea and Cerro Prieto data sets plot on the same trends and overlap completely on the figure, as expected since both fields are operating in the same fluvial-deltaic stratigraphic section of the ancestral Colorado River. Again the lower relative permeabilities of siltstones as compared to sandstones is apparent, and again, the siltstones that are highly epidote-enriched plot well up into the adjacent sandstone field. A linear least squares fit through all lithologies for the Salton Sea Geothermal Field (dashed line in figure) yields the line: $\text{Log}_{10}(\text{permeability in mD}) = -2.075 + 0.149(\text{porosity in } \%)$, ($R=0.81$); while a similar fit through all lithologies from both the Salton Sea and Cerro Prieto Geothermal Fields (solid line in figure) yields the line: $\text{Log}_{10}(\text{permeability in mD}) = -2.091 + 0.145(\text{porosity in } \%)$, ($R=0.85$). Both equations are effectively identical, and are similar to a line generated by Intercorp (1978, cited in Seamount, 1981) on core from the East Mesa Geothermal System.

Sonic Velocity

Compressional wave velocities were measured parallel to the axis of those 1 inch subcores that were completely unfractured, on pieces at least 2 inches long. The measurements were made on a velocity bench on loan from the U. S. Bureau of Mines at Morgantown, W. Va. as part of the DOE funded Eastern Gas Shales Project. All measurements are the average of 10 individual measurements made after stabilization of wave forms, and in all cases, these well indurated rocks yielded sharp, rectangular waveforms and measurement uncertainties of <2%. The actual measurements were made by H. Gertje, Lab technician in the Geological Engineering facility at Michigan Tech.

Figure 17. Variation of permeability ($\text{Log}_{10}K$ in milliDarcies) with Porosity (Vol %) for all Salton Sea geothermal wells (this investigation and McDowell, 1984 and unpublished) and geothermal wells from Cerro Prieto Geothermal Field (Seamount, 1982; Lyons and van de Kamp, 1981). Filled circles for sandstones, open triangles for siltstones, E for epidotized samples. Linear least squares lines for all data (solid line) or for Salton Sea field data only (dashed line). See text for equations.

Figure 18. Variation of compressional wave velocity in Km/sec with depth (m). Rectangle for mudstone, + for siltstone, Diamond for sandstone, for SDH.

Figure 19. Variation of compressional wave velocity in Km/sec with Bulk Density (g/cc) for all lithologies from SDH. Curve shown for typical sediments and sedimentary rocks from Grant and West (1965).

The actual P-wave velocities that could be measured have been summarized in Tables 1, 2, and 3. As indicated in Figure 18, the sonic velocities increase with increasing depth, and show a strong lithologic effect. At depths near 1000m, the velocities increase from sandstone to siltstone to mudstone as the bulk density of the rocks increases, yielding velocities of 2.7, 3.4, and 4.0 Km/sec., respectively. The lack of unfractured subcore at depths >2000m made velocity measurements of biotite zone lithologies impossible with the samples available. As indicated in Figure 19, however, the measured compressional wave velocities vary with bulk density along a curve typical of sediments and sedimentary rocks. In light of the limited number of sonic velocity measurements, velocity-depth curves can be constructed more accurately from the standard sediment bulk density-velocity relationship shown in Figure 19 and the larger bulk density data set.

A series of compressional wave velocities were made on a single piece of full sized SDH mudstone core to determine if any horizontal velocity anisotropy exists in the altered sediments that might reflect stress anisotropies in the system. Ten velocity determinations were made at 30 degree angular increments around the core, and each series of measurements was repeated twice. The maximum percentage change in velocity was 2.1 and 1.8% for the two sets of measurements, effectively identical to the normal measurement uncertainty for such angular measurement sequences based on the measurement of a very large number of Eastern U. S. gas shale cores. However, the two sequences of measurements gave identical patterns of velocity change with angle, and the wave forms were both very stable and of almost ideal rectangular form relative to the bulk of gas shale measurements. Thus it is possible that this velocity variation of 2%, though small, is real and reflects a corresponding horizontal stress anisotropy in this tectonically active volume of rocks.

SECTION 2A:

RECONNAISSANCE PETROLOGY OF ALTERED SILTSTONE AND SANDSTONE

The general alteration mineralogy observed in the SDH is identical to that observed in cuttings in the field interior (McDowell and Elders, 1979, 1980; McDowell, 1987). Chlorite zone assemblages are observed from the shallowest samples investigated (473.4m) to the biotite isograd near 1980m, while biotite zone assemblages persist to the base of the well. The chlorite zone may be divided into two subzones, an upper chlorite-calcite zone at depths less than about 950m, and a deeper chlorite-calcite-epidote zone. The presence of very calcite-rich siltstones, but not sandstones, at depths less than 1065m, is suggestive of a transition upward to a calcite-cemented caprock. Unlike the very abrupt transition from porous chlorite zone to caprock in the interior wells, the shallow portions of the SDH have the overall characteristics of a flank well just off the main part of the field where a very broad transition from chlorite zone to caprock occurs (McDowell and Paces, 1985; McDowell, 1987). The volume percentage of minerals based on quantitative XRD analyses and thin section reconnaissance modes has been summarized in Tables 4 and 5, respectively.

Chlorite Zone

The authigenic mineralogy of the chlorite zone consists of calcite, chlorite or epidote cement, quartz, albite, and K-feldspar overgrowths, illite as a minor cement and as an alteration product of detrital feldspar, and minor pyrite and sphene. The content of the cementing phases varies widely (Figure 20), and there is a tendency to produce rocks in which one phase is dominant, or in which none of these phases is present. Calcite and chlorite are strongly inversely correlated, although even in the most calcite-rich sandstones, trace amounts of chlorite are still present. At depths >1300m, where epidote contents >1% are observed, chlorite is present in trace amounts at all calcite contents, but does not appear to coexist stably with calcite.

The first authigenic feldspar that forms discrete, minute (<10micron) grains in pore spaces is observed at 940.3m. In the 940 to 1300m interval, both pore-filling aggregates of <0.01mm feldspar and thin feldspar overgrowths become a minor but persistent feature of the clastic rocks. Even in detrital grains that show clear evidence of dissolution, thin discontinuous authigenic overgrowths on parts of the grains are noted. Abruptly at 1300m, and at all greater depths, feldspar becomes a significant cementing phase in sandstone, and in siltstones patchy aggregates of authigenic feldspar up to 5mm across are observed. Many former detrital feldspars have been completely replaced by aggregates of authigenic feldspar, and internal features common to the detrital feldspars, such as overgrowths with identifiable inner boundaries, are less commonly observed. This suggests that significant recrystallization of the detrital feldspars has occurred at depths >1300m. Both albite and K-feldspar appear to be stable at most depths >940m, consistent with their early appearance in the chlorite zone of the interior wells (McDowell, 1986). However, in the interval from 1300m to the biotite isograd, K-feldspar is the major precipitating feldspar, and in strongly epidotized sandstones and siltstones, albite is often not observed.

Calcite is particularly abundant in siltstone of the chlorite-

Figure 20. Variation in vol % calcite (open circles) and Epidote (filled circles) with depth (Km) in SDH. Biotite-chlorite zone boundary indicated by dashed line. Only rocks with >0 % epidote plotted at depths <1.3 Km for clarity, rocks with 0 % calcite plotted at all depths.

TABLE 4A Volume % Minerals in Mudstone from quantitative XRD

Depth (m)	Qtz	Plag	Ksp	Mica ₁	Chl	Calc	Py	Ep	Ah
754.4	30.6	7.6	6.3	25.6	26.0	1.0	2.9		
912.1			63.3		31.9		4.8		
940.9	30.1	9.0	26.9		33.9				
962.5			66.6		32.1		1.3		
1059.4	22.5	15.9	7.2	20.7	14.3	11.4			
1064.5	21.8	16.0	6.0	36.3	12.3	7.3	0.3		
1064.7	26.6	21.9	10.5	17.4	11.6	12.1			
1157.3	23.8	17.2	7.6	33.5	11.8	5.6	0.6		
1161.9	21.4	13.6	11.4	35.2	6.0	8.3	4.1		
1163.4	24.2	18.9	7.3	28.6	13.0	7.6	0.3		
1166.1	5.9	3.9	3.4	11.2	34.5	41.1			
1224.5	20.4	10.0	4.4	37.9	6.6	18.6	2.2		
1225.8	19.7	11.2	2.8	44.9	7.4	10.0	3.9		
1227.9	21.9	11.9	4.2	37.9	9.9	13.4	0.8		
1235.6	21.8	8.7	3.0	43.1	16.3	7.2			
1238.8	21.1	13.7	3.3	32.1	12.2	17.2	0.4		
1300.0	16.8	12.9	32.7	6.0	28.6	2.5	0.5		
1308.0			75.2		21.5		3.4		
1312.3	11.8	9.1	38.9		38.1	1.5	0.6		
1312.7	17.7		41.9	16.2	21.9	1.8	0.6		
1315.9	16.7		40.9	11.9	14.4	15.5	0.7		
1316.1	16.4	5.5	12.0	19.4	28.7	17.4	0.7		
1318.0	19.9	17.1	42.9		3.3	13.8	2.9		
1320.2	22.8	8.1	14.8	26.5	13.8	10.4		3.6	
1321.6	24.5	5.9	7.1	34.2	13.4	10.6		4.3	
1322.1	24.1	6.1	10.1	27.1	10.1	7.0		15.5	
1582.0	21.5	21.1	10.6	17.5	9.9	19.4			
1699.2	24.5	23.4	17.5		32.8		1.7		
1837.5	20.3	30.3	20.2	5.0	16.4	7.9			
1838.8	18.2	30.5	20.3	15.0	13.8	2.1			
1840.4	10.0	26.9	28.9		32.9	1.3			
1985.2	7.3	32.5	47.9		12.3				
2097.2	17.4	15.2	7.4	14.6	7.8	12.0	23.4		2.3
2164.1	28.4	22.4	5.3	29.4	8.1	6.4			
2166.1	30.2	20.3	4.8	22.9	10.8	11.0			
2225.6	11.2	20.6	36.5	3.5	15.2		4.0	8.9	
2226.3	14.4	29.3	29.0		26.0		0.5		
2300.3	21.3	26.6	12.0	21.4	14.2	4.5			
2480.4	20.5	34.8	20.0	15.2	5.9	1.9	1.6		
2486.3	15.5	31.4	19.8	16.3	10.4	6.6			
2682.2	20.0	33.2	14.8	*16.9	10.0	5.0			
2819.8	13.3	36.6	18.5	*25.5	6.1				

1-Illite except those marked by * = Biotite.

TABLE 4B Volume % Minerals in Siltstone from quantitative XRD

Depth (m)	Qtz	Plag	Ksp	Mica ₁	Chl	Calc	Py	Ep	Hem	Act	Ah
604.8	22.2	11.4	21.4	22.9	13.0	8.1	0.9				
608.4	25.1	14.1	6.6	31.1	13.9	8.8	0.3				
748.8	30.3	16.8	10.5	23.6	11.3	7.5					
1062.1	26.1	20.4	10.3	18.2	14.1	10.9					
1155.6	20.2	16.9	7.5	23.8	10.6	0.6					3.8
1157.4	30.2	23.0	11.0	4.9	13.6	11.4					
1162.5	26.3	23.2	9.0	26.3	10.0	3.8	0.9				0.5
1168.1	25.8	19.1	8.9	10.1	21.9	12.7	1.5				
1170.8	24.4	22.3	11.5	24.9	9.0	5.9	1.2				0.7
1222.1	23.5	10.3		40.5	6.6	10.0	9.1				
1225.5	21.7	9.4	3.5	33.6	18.0	10.2	1.3				2.4
1233.8	23.1	12.8		43.0	11.9	9.3					
1293.3	19.3	21.5	40.3		9.3	8.2	1.4				
1304.2	40.2	12.3	29.1		1.3	15.4	1.7				
1317.8	26.9	25.5	23.2		12.8	10.0	1.7				
1415.3	20.8	19.4	30.8		15.3		1.6	12.1			
1420.4	30.2		23.8		22.9			23.2			
1427.0	41.7		23.5		1.4			12.8	20.7		
1427.1	12.5		64.4		28.0						
1839.3	18.4	31.3	29.8		16.6	3.9					
1984.2	11.8	24.7	44.0		16.7	2.8					
1984.6	23.3	17.8	7.1	*17.6	23.5			10.7			
2060.5	13.8	29.6	34.7		13.8		2.7	5.5			
2483.1	13.5	23.3	8.7	*32.7	2.8			15.4		3.7	

1-Illite except those marked by * = Biotite.

TABLE 4C Volume % Minerals in Sandstone from quantitative XRD

Depth (m)	Qtz	Plag	Ksp	Mica ₁	Chl	Calc	Py	Ep
473.5	43.5	24.6	15.0	8.7	7.4	0.6	0.2	
955.7	59.7	5.2	23.0		11.1	0.6	0.4	
957.8	52.6	6.4	23.4		16.7	0.5	0.5	
961.1	47.8	15.1	25.1		11.1	0.9		
1160.3	41.9	28.1	19.6		9.9	0.5		
1164.1	44.2	22.8	13.5	3.4	5.5	10.6		
1305.2	62.0		25.8		9.4	0.7	2.1	
1308.8	69.9		23.3		4.8	0.7	1.3	
1311.3	45.7		33.5		11.1	8.8	0.9	
1419.8	48.4		17.2		4.2			30.2
1425.9	45.1		31.6		3.7		3.0	
1837.7	27.3	20.4	5.2		23.3	23.1	0.5	

1-Illite only.

TABLE 5 RECONNAISSANCE MODES OF SILTSTONE AND SANDSTONE (VOL %)

Depth (m)	Qtz + Feld	Calc	Pore	Chl	Ill Bio*	Ep	Act	Opg + Sph	Ah
SILTSTONE									
958.0	36	0	7	54	13	0	0	3	0
1304.2	69	13	14	tr	0	2	0	2	0
1317.9	64	22	10	tr	1	tr	0	3	0
1415.4	75	0	13	1	0	8	0	3	0
1839.3	72	20	5	2	0	tr	0	3	0
1984.5	15	0	17	tr	tr	68	0	0	0
2225.2	33	0	21	tr	0	46	0	0	0
2301.3	27	0	23	0	0	50	0	0	0
2483.1	11	0	15	0	0	70	4	0	0
2683.2	61	37	0	0	0	0	0	2	0
2887.8	62	0	2	5	5*	28	0	3	0
2887.8	55	0	0	tr	11*	32	0	2	0
2955.5	74	0	0	8	13*	1	0	4	0
SANDSTONE									
473.4	64	6	29	tr	tr	0	0	1	0
747.0	64	16	19	1	tr	0	0	0	0
940.3	78	0	15	7	0	tr	0	0	0
953.1	69	0	14	17	0	0	0	0	0
955.7	70	0	17	12	0	tr	0	1	0
958.0	53	0	10	37	0	tr	0	0	0
958.8	67	1	26	6	0	tr	0	0	0
961.1	74	0	18	8	0	tr	0	0	0
1160.3	76	0	12	11	0	1	0	0	0
1164.2	62	14	20	3	0	1	0	0	0
1305.2	79	1	14	2	0	3	0	1	0
1308.8	90	0	9	1	0	tr	0	0	0
1311.2	74	10	15	tr	tr	tr	0	1	0
1419.8	71	0	7	0	0	22	0	0	0
1426.1	80	0	7	1	0	11	0	1	0
1837.7	37	62	1	tr	0	0	0	0	0
2618.4	81	0	14	0	0	5	0	0	0
2618.5	82	0	13	0	0	5	0	0	0
2772.2A	68	0	2	tr	tr*	22	0	1	8
2772.2B	75	0	1	tr	tr*	23	0	1	tr
2954.8A	78	0	1	tr	1*	17	0	1	3
2954.8B	77	0	3	tr	0	15	0	0	5
2955.5	76	0	0	7	9*	4	0	4	0
3020.0	33	0	5	0	0	49	13	0	0

tr = trace amount <1%. Modes based on 500 counts/sample.

calcite subzone, ranging up to 22 volume %, with the result that porosities of the siltstones are relatively low. In sandstone, the calcite cement is often very patchy, and thin sections cut immediately adjacent to each other may have widely differing calcite contents. Cementing calcite ranges from micrite through microspar to sparry calcite which encloses other detrital phases. It is typically colorless, although various shades of red-brown coloring are also observed.

Chlorite is most abundant at <1164m depth, but persists throughout the entire chlorite zone. It ranges in color from pale green-brown to light green or yellow green, and typically consists of books or loose radially arranged plates less than 0.05mm in length. These plates tend to be more randomly oriented and finer grained in the shallower parts of the chlorite zone. It shows anomalous blue pleochroism in most cases, although anomalous brown colors are occasionally observed.

Illite is present throughout much of the chlorite zone, mainly as an alteration product of detrital feldspar, where individual flakes up to 0.05mm in length are observed. Some feldspars have been completely replaced by porous aggregates of illite with minor chlorite and feldspar. In other cases, very fine grained illite-chlorite masses have evolved from altered detrital mudstone clasts. With the exception of the shallowest siltstone investigated, illite is not a major pore filling matrix phase. In sandstone, illite as a detrital feldspar alteration product is last observed at 1157.4m, while in silty mudstone the last optically identifiable illite occurs at 1293.3m. Below these depths white mica is rarely observed, with the single exception of a siltstone at 1317.9m that contains plates of clear, idioblastic white mica up to 0.1mm in length. These are very similar in appearance to authigenic muscovite in Elmore 1 (McDowell and Elders, 1980). By analogy with Elmore 1, this suggests temperatures near 300°C. at depths near 1300m in the SDH.

Epidote is first detected at 950.8m in siltstone and 939.9m in sandstone, while it was not observed in these lithologies at 749 and 747m, respectively. Cho et al (1987) report epidote in sandstone at 906m, near the top of the third cored interval, suggesting that epidote first appears somewhere between the second and third cored intervals, at temperatures near 230°C.. As in the interior wells, the first epidote observed forms minute (<0.01mm) idioblastic blades or rods that occasionally form rosettes or fan-shaped arrays. Epidote contents are typically in the trace to 3 % range throughout the chlorite zone, although at depths of 1419.8m or more, percentages of up to 30 % occur in sandstone. As epidote increases, both calcite and chlorite decrease (Figure 20). Where the epidote contents are high, the epidote forms a coarsely crystalline cement that often completely fills individual pore spaces and shows clear evidence of replacement of both quartz and feldspar. On occasion, two generations of epidote are noted -an earlier coarsely crystalline phase, and a later generation which forms long, fine needles that often grow outward from the surface of the earlier grains and into open pore space. Epidote color varies with depth from pleochroic clear to light green shallower in the chlorite zone to a deeper yellow-green color at greater depths.

Biotite Zone

The Biotite Isograd

The dominant characteristic of the biotite isograd in the wells examined thus far is not the appearance of biotite, but the abrupt disappearance of calcite cement from sandstone. In some wells, this disappearance is marked immediately by the appearance of small amounts of fine-grained, pale green or green-brown, blocky biotite books that line pore walls and often form intergranular films along framework grain boundaries. In other wells, the first biotite detected occurs as very rare aggregates of minute biotite books at the limit of microscopic resolution, at depths of up to 200m deeper than the depth at which calcite disappears. Examination of additional cuttings in such wells almost invariably results in biotite being detected at progressively shallower depths approaching those where calcite disappears. These characteristics are entirely consistent with the difficulty of defining the position of the biotite isograd in regionally metamorphosed rocks.

The biotite isograd in the SDH is similar in character to the second case described above. Calcite is last observed in sandstone at 1837.7m and in siltstone at 1984.2m, while the first significant biotite is observed in these lithologies at 2772.2m and 2887.8m, respectively. Trace amounts of biotite have been identified in siltstone at 1984.5m in the form of a single aggregate of blocky, very pale green-brown grains. All other sandstones and siltstones examined between 1984.5m and 2772.2m were free of biotite and calcite with the exception of a single, very calcite-rich siltstone (Table 1) at 2683.2m. In addition to this anomalous assemblage, a second sandstone at 2955.5m depth shows lower temperature characteristics including the presence of detrital quartz and feldspar morphologies, and of detrital muscovite, as well as evidence of alteration of detrital feldspar to illite.

The presence of anomalous, lower temperature assemblages in the biotite zone illustrates another characteristic of most geothermal wells. Intervals with chlorite zone assemblages or textural characteristics are sporadically observed within the biotite zone in the field interior. Calcite in such intervals (Kendall, 1976) has heavier oxygen isotope ratios typical of calcite equilibrated at lower temperatures. Kendall noted that these anomalous samples are almost invariably located within thick mudstone-rich stratigraphic intervals, suggesting a lack of equilibration in the minor interbedded sandstones or siltstones that reflected the low effective permeability of the surrounding mudstones. The extent of isotopic equilibration with the geothermal brines increases in the order mudstone<siltstone<sandstone=vein (Kendall, 1976). The anomalous assemblages in the SDH appears to be another example of such lack of equilibration, as the coarser clastics are scarce at all depths greater than 2000m in the SDH.

Sturtevant and Williams (1987) note that calcite from all lithologies is isotopically identical in the 460 to 1500m interval, implying extensive reequilibration of the sediments in the upper part of the SDH within the shallow chlorite zone. The pervasiveness of this reequilibration is high even in comparison with the most altered interior wells, which invariably have multiple unequilibrated intervals in both the chlorite and biotite zones (Kendall, 1976; Olsen, unpublished data). The unusually high degree of reaction noted by Sturtevant and Williams (1987) in the shallow chlorite zone is entirely consistent

with the high percentage of sandstone and siltstone is this part of the well. Conversely, the appearance of anomalous, low temperature assemblages in the biotite zone is consistent with the lack of coarse clastic rocks at these depths.

General Characteristics of the Biotite Zone

The characteristic mineral assemblage of the biotite zone is quartz, albite, and K-feldspar, epidote in large amounts, biotite, chlorite, and actinolite in lower but variable quantities, and trace amounts of pyrite and sphene. Both sandstones and siltstones containing only biotite, or chlorite, or actinolite are observed, as well as rocks with the mineral pair biotite + chlorite. Rocks containing chlorite + actinolite or biotite + actinolite were not observed. Biotite is particularly abundant at depths >2885m, where it ranges up to 13% in siltstone and 9% in sandstone. Chlorite is present in these deep siltstones, strongly suggesting that chlorite is stable at least to 3000m in the SDH. In fact, more samples contain chlorite than contain either biotite or actinolite in the biotite zone of the SDH. The general appearance of chlorite in the biotite zone is similar to that in the chlorite zone, although it is slightly coarser. Since chlorite does not disappear from biotite zone mudstones and siltstones in the field interior until the temperature is over 345°C., temperatures in the SDH have presumably not exceeded that value by 3000m depth.

Actinolite is first noted in siltstone at 2483.1m in the form of mats of fine hair-like, often curved fibers that are significantly less than 0.1 micron thick. It was not detected in sandstone until 3020m depth, in an epidotized sandstone. In other wells in the geothermal system, the first appearance of actinolite is like that of biotite in being very hard to define, and either actinolite or biotite may appear at a shallower depth. Like biotite, however, it does not appear until calcite disappears.

Epidote is the major alteration phase in the biotite zone, and occurs as coarse pore-filling aggregates with a highly variable distribution in thin section. It is particularly abundant in siltstone, where it makes up 28 to 70% of the rock (Tables 4 and 5, Figure 20). Despite the high epidote content, the porosity of siltstone in the 1984-2483m interval remains high, as much of the epidote forms at the expense of quartz and feldspar, and clear evidence of local solution of these phases exists. The presence throughout the biotite zone of patches of authigenic feldspar, and discontinuous overgrowths on quartz, however, indicates that these phases are still stable. This suggests that detrital phases with non-equilibrium states of Al-Si ordering or stored strain are being replaced by epidote or dissolving, while authigenic feldspar with equilibrium ordering and strain-free quartz are precipitating elsewhere. Shearer et al (1987) note on an XRD basis that K-feldspar becomes progressively more disordered with increasing depth in the SDH. McDowell (1986), using 2V measurements on authigenic feldspar overgrowths and pore-filling aggregates from Elmore 1, noted that albite, and possibly K-feldspar, showed increasing disorder on increasing temperature. The ordering state as well as the composition of the detrital feldspars was often quite different from that of the authigenic phases.

In the samples investigated by us, anhydrite appears in the coarser clastic rocks at depths of 2772.2, 2948.7, and 2954.8m, where it occurs

as a patchy cement that is being replaced by epidote. It is also present as lenses surrounded by calcite in silty mudstone at 1235.6m, laminations of evaporitic origin in mudstone at 2745.5m, and in a vein in mudstone where it is also being replaced by epidote. The erratic distribution of anhydrite, and the fact that it is being replaced by one of the major authigenic phases, suggests that much of the anhydrite cement originated early in the history of the geothermal system by solution of evaporite units and local precipitation in the coarser clastics rocks that were nearby. This late diagenetic/early geothermal origin for anhydrite as a cement is consistent with the observation that it is being replaced by a variety of authigenic phases including calcite, epidote, feldspar, and biotite in various interior wells. Its irregular distribution is also consistent with the widespread but erratic distribution of anhydrite-rich evaporitic units (McKibben and Elders, 1985; McKibben et al, 1987) throughout the fluvial-deltaic section.

SECTION 2B: REACTIONS AND MASS CHANGES IN THE ALTERED SEDIMENTS

Introduction

As part of a separate investigation of geochemical changes that occurred during alteration across the geothermal system (McDowell, 1984; McDowell and Bornhorst, 1985), a very large number of XRF analyses on cuttings have been obtained from 9 different wells. Using this database, the absolute elemental gains and losses from mudstone have been determined through the chlorite and biotite zones, using as a parent the average low temperature mudstone from wells in the Westmoreland and Niland Areas, and assuming immobility of selected trace elements. These calculations indicate significant absolute gains of K and Fe + Mg, and losses of Ca, Si, and Al from mudstones in the chlorite and biotite zones.

In order to compare the results obtained in this investigation on the SDH to the geochemical mass changes observed in the interior of the field, a series of simplified calculations has been carried out using the existing data set. For each rock type, the mineral proportions of a parent rock have been estimated using the data for the well-sampled shallow chlorite zone. The changes in major element composition have then been calculated relative to 100 cc of the parent rock, including pore space, by using the XRD and model data in combination with the known mineral compositions of the various major mineral phases as obtained from other investigations (McDowell and Elders, 1980, 1983; McDowell and McCurry, 1977; McDowell and Paces, 1985; McDowell, 1986; Yau, 1986; Donaghe, personal communication, 1986, 1987; Cho et al, 1987; Chou and Williams, 1987). The overall objective is to determine the approximate major element changes in the various rock types in the SDH during alteration, and to see if these changes are consistent with the changes observed for these same elements in the field interior.

The least altered sediments may be described in terms of four major components: Framework minerals (mainly quartz and feldspar); layer silicate minerals (mainly smectite or illite); cement minerals (mainly carbonate); and a heavy mineral suite. Based on a very large number of XRF and XRD analyses from wells within and adjacent to the geothermal system, it is clear that the mudstones were initially exceedingly homogeneous in composition, including very constant trace element contents. Thus it is possible to determine a realistic parental composition for the rocks that make up the finest grain size fraction in the system, and there is a reasonable assurance that this parent can be used at all depths <2600 m.. In addition, the XRD analyses indicate that the relative proportion of quartz, plagioclase, and alkali feldspar in the parental framework component is approximately the same across the entire grain size spectrum from mudstone to sandstone. Sediments of all grain sizes may be described in general terms as mixtures of varying proportions of the framework and layer silicate components, to which cement has been added in various proportions depending on the available porosity.

In practice, while a parent composition may be confidently assigned to the finest grained rocks, it is far more difficult to determine a reasonable composition for the coarser grained sediments. The cleanest, most matrix-free sandstones may be reasonably assigned a parent composition in terms of mineral proportions and major element

composition. But subtle variations in the heavy mineral content during sedimentation yield extremely large variations in those trace elements associated with the heavy minerals. The resulting large standard deviations assigned to the parental sandstone trace element averages tend to mask many of the changes due to alteration. In general, resort must be made to very general averages of restricted grades of alteration which may then be intercompared to obtain a feel for trends in alteration. Since in fact such clean sandstones make up a very small portion of the sandstones, this limited data set can only describe alteration in a very small fraction of the system. The majority of sandstones and siltstones contain a significant and highly variable proportion of both layer silicate matrix and heavy minerals. In the case of core, it is exceedingly difficult to assign an altered siltstone to any particular parent siltstone, let alone to accurately determine a reasonable parental siltstone or slightly argillaceous sandstone.

In the discussion that follows, the geochemical changes due to alteration in the SDH will be discussed for the various lithologies.

Mudstone Alteration

The average mineral content of shallow chlorite zone mudstone in the SDH is generally similar to that observed in mudstone from the same grade in the interior of the field (Table 6). While quartz is slightly less and K-feldspar slightly greater in the SDH mudstones, the only significant difference is that the albite content of the SDH mudstone is almost twice that observed in the field interior. In the latter mudstones, such high albite contents are not observed until the deepest third of the chlorite zone, where K-feldspar is also higher and illite significantly lower. Since relatively unaltered mudstones, both east and southwest of the SDH, also have plagioclase contents near 5%, the high albite content in these low grade SDH mudstones may be due to alteration, not sedimentological variation. This is consistent with the observations of Donaghe and Peacor (1987) that almost all framework plagioclase in the mudstones examined was albite, in sharp contrast to the much coarser detrital plagioclase from sandstone in the field interior, where calcic plagioclase with non-equilibrium states of order is preserved well into the biotite zone (McDowell and Elders, 1980; McDowell, 1986). This slight albitization of the mudstones, with relatively few changes in the content of other minerals, is distinctive.

The majority of the mudstones examined in this investigation are in fact silty mudstones that are transitional to very fine siltstone, and many of the samples have been termed siltstones in the core lithologic descriptions of Mehagan et al (1987). In terms of degree of alteration, fluid transport, and petrophysical properties, however, the sediments in the grain size range from true mudstone to very fine siltstone behave in a similar manner as a group. Their behavior contrasts sharply with all rocks with grain sizes $>0.01\text{mm}$, in the sandy siltstone and sandstone size ranges, which act as much more open systems and show distinctively different patterns of alteration and geochemical change.

TABLE 6 : Average Shallow Chlorite Zone
Mudstone, SDH and Interior Wells

	Shallow Chl Zone Average Mudstone # in Avg (11)		Range of Average Chl Zone Mudstones In Field Interior (53)	
	Avg	SD		
Qtz	22.3	2.6	26.9 -	35.5
Ab	9.2	4.0	3.6 -	5.2
Ksp	5.4	3.3	2.3 -	4.9
Ill	33.8	7.6	27.4 -	39.2
Chl	14.7	3.3	12.3 -	20.6
Calc	12.3	4.2	8.4 -	15.0
Py	2.3	1.5	0.0 -	0.7

Total 100.0 Wt. %

Average Shallow Chlorite zone mudstone mineralogy in Wt. % of SDH relative to range of averages of shallow chlorite zone mudstones from 6 different wells in field interior. SDH quantitative XRD analyses have been adjusted to XRD values before recalibration of XRD system at UC Riverside in 1986 to make them consistent with older XRD analyses from field interior wells.

Figure 21. Variation in vol % minerals for all mudstones in the 912 to 1320 meter depth range that lie within 3 m of sandstone, plotted as function of distance to nearest sandstone in meters. Shaded area in each figure shows normal range for that mineral in mudstones that are >3 m from sandstone in this part of the shallow chlorite zone. The plotted minerals include Or (=Ksp) in A, Pyrite in B, Chlorite in C, Albite in D, Illite in E, quartz in F, and Calcite in G.

Figure 22. Variation of vol % minerals with porosity for altered mudstones of Figure 21. Shaded area indicates normal range in % mineral and porosity for shallow chlorite zone mudstones located >3 meters from sandstone. See Figure 21 and text for details. Plotted minerals include Chlorite in A, Calcite in B, Illite in C, and Ksp in D.

Figure 23. Variation in number of mMols of elements gained (+) or lost (-) relative to normal shallow chlorite zone mudstone, plotted as a function of distance to nearest sandstone, for the altered mudstones of Figure 21. Vertical bars indicate variation in indicated elements for normal shallow chlorite zone mudstones located >3m from sandstone. Solid and open circles are, respectively, K and Al in A, Fm (=Fe + Mg) and Si in B, Ca and Na in C. Normal variation for Si in B plots off scale as indicated by arrows and mMols Si at limits of variation.

K-feldspar-chlorite Mudstones

Within the shallow chlorite zone of the SDH, several distinctive mudstones occur which consist entirely of K-feldspar, chlorite, and minor pyrite. All these unique mudstones are located close to sandstone, and as indicated in figure 21, there is a systematic change in mineralogy as a function of the distance to the nearest sandstone as measured from the detailed core lithologic descriptions of Herzig et al (1987). The calcite content is particularly critical (figure 22B). Mudstones with more than 5% calcite generally have porosities in the normal range for this depth, and near normal contents of chlorite, quartz, illite, and K-feldspar. Once calcite has been reduced to <5% and porosities increased above 6%, the chlorite and K-feldspar contents increase dramatically, while albite, illite, and quartz decrease abruptly to zero. Where significant calcite is present, the operative reaction appears to be a near Al-conservative reaction similar to

Once calcite is removed, however, open system reactions dominate and very large mass changes occur during alteration. Chlorite in particular is strongly correlated with porosity (figure 22A), implying that significant fluid transport is necessary to supply the Fe and Mg required to form chlorite. The high porosity associated with high chlorite content is consistent with SEM observations on authigenic chlorite (Kramer, 1986) which show equant, hexagonal chlorite books forming very loose, open 3 dimensional skeletal frameworks in the pore spaces.

There is a suggestion, based on calcite contents within 1m of sandstone that are higher than average, that calcite removed from one mudstone may, at least in part, precipitate in nearby mudstone, thereby decreasing the permeability of these mudstones and thus temporarily preventing further reaction. Thus, within 0.5m of sandstone, more calcite rich mudstones have significantly higher illite, quartz, or albite contents than do adjacent, low-calcite mudstones. In general, as the distance to the nearest sandstone decreases, albite and illite disappear first, and quartz next, although all significant reaction occurs within 1m of the sandstone. The mudstone porosity increases from an average of 4.7 % in unaltered rock to an average of 10.3% within 0.2m of sandstone, with individual porosities up to 16%.

The changes in the major element composition of mudstones as a function of distance to the nearest sandstone have been calculated in millimoles relative to 100 cubic cm of average mudstone parent, including pore space, and are shown in figure 23. The chlorite-K-feldspar mudstone nearest sandstone has also been listed in Table 7b.

Figure 23 clearly shows major elemental changes in mudstones adjacent to sandstone. The K content is increased by over 300 mMols, a 115% increase relative to the parental mudstone, while Fm (= Fe + Mg) is also doubled in amount relative to the original mudstone, a 400 mMol increase. At the same time, 100% of the original Na and Ca (and CO₂) are lost, yielding losses of 136 and 279 mMols, respectively. All of these changes are significant in that the percentage change relative to the mudstone parent is much greater than the variation in the content of these same elements due to the normal variations of mudstone mineralogy (shaded areas in Figure 23) . Typically such normal

TABLE 7 Mass Changes of Altered Mudstones

	Parent a	b	c	d	e	f	g	h
	(11)	1308	1985.2	1322.1	(5)	1840.4	(2)	(9)
Pore	4.7	8.0	3.0	4.0	4.0	7.0	0	0
Qtz	21.7	0	7.1	23.1	18.2	9.3	29.3	18.0
Ab	13.6	0	31.5	5.9	25.4	25.0	21.3	27.8
Ksp	5.9	69.2	46.5	9.7	18.7	26.9	5.0	18.2
Ill	32.5	0	0	26.0	7.2	0	26.2	0
Bio	0	0	0	0	0	0	0	15.9
Chl	10.4	19.7	12.9	9.7	20.3	30.6	9.5	11.6
Calc	10.4	0	0	6.7	5.9	1.2	8.7	4.1
Py	1.1	3.1	0	0	0.3	0	0	3.3
Ep	0	0	0	14.9	0	0	0	1.0

Change in mMols relative to 100cc parent mudstone

Si	-	-173	+347	-208	+164	-21	+401	+266
Al	-	-62	-30	-165	-130	-95	-51	-212
Na	-	-136	+179	-77	+118	+114	+77	+142
K	-	+352	+143	-10	-60	-37	-51	-12
Fm	-	+217	-98	+25	+169	+352	-83	+352
Ca	-	-279	-279	+116	-122	-249	-43	-168
CO ₂	-	-279	-279	-98	-122	-249	-43	-168
H ₂ O	-	-50	-198	-4	+14	+162	-59	-98

Mineralogy (Vol %) of selected individual (depth given in m) or average (# analyses in avg noted) rock type, and calculated compositional changes relative to shallow chlorite zone parent (a) in mMols/100cc parent. Endmember mineral compositions used, Fe + Mg = Fm, O₁₀ basis for layer silicates, chlorite = Fm₂Al₂Si₃... basis, epidote as ..Al₂Fm..basis, illite as KFm_{0.4}Al_{2.6}Si₃...basis.

mineralogic variations yield changes of about 30% relative to the average composition of the parental mudstone.

The calculations also indicate Al losses of about 19% or 165 mMols, and losses of 8 to 20 % Si or 200 to about 500 mMols, relative to the parent. These changes are well within the range expected due to the observed normal mineralogic variations, but could still represent real mass changes. All 8 mudstones within 1m of sandstone show Al losses, while 6 of 8 mudstones indicate Si depletion. Significant Al mobility is quite plausible in light of the widespread distribution of feldspar as a vein mineral, and the extreme epidotization of many sandstones throughout the geothermal system.

In fact, the gradual elemental gains and losses observed for all mudstones across a depth range of nearly 1 Km and a temperature range of 220 to 340°C. are grossly similar to the changes observed in those mudstones located within 1 m of sandstone from the shallow portions of the chlorite zone in the SDH. In the case of the chlorite-calcite mudstones in the SDH, fluid movement through the sandstone, and leaching and reaction of the adjacent mudstone was effectively confined to a 1 m thick zone on either side of the aquifer. Mudstone further away from the sandstone shows normal shallow chlorite zone mineral assemblages like those observed throughout the geothermal field. With the exception of Na, the changes observed in that 1m alteration zone mirror the pervasive changes that operated in the interior of the geothermal system that gave rise to complete alteration of almost all mudstones in the entire sedimentary pile. Mudstones from the field interior gain in albite and Na throughout the deeper chlorite and shallow biotite zones.

Chlorite Zone Mudstone

A typical alteration pattern in the field interior is cementation by epidote in the deeper portions of the chlorite zone, in combination with significant increases in both albite and K-feldspar. Excluding vein epidote, very few mudstones with significant epidote were sampled in the present investigation, although siltstones and sandstones are extensively epidotized in the SDH. The mineralogy and alteration of a single mudstone (at 1322m depth) with significant epidote (14.9%) is shown in Table 7d. Again Si, Al and Na losses are indicated, while Ca is gained because significant calcite remains even though a large amount of epidote has been added to this particular mudstone. The observed decreases in calcite and illite, and gains in quartz are consistent with observations elsewhere in the geothermal system that indicate that the simplest reaction that can be written to represent continuous epidote formation in the chlorite zone is:

This mudstone occurs at the base of one cored interval, and the next deeper cored interval is made up almost entirely of highly epidotized siltstone and sandstone, with epidote contents ranging from 17 to 64 %. In light of the relatively low epidote contents of mudstone in this well, the high epidote content in this shallow mudstone again seems to suggest significant reaction of mudstone located near major

sandstone aquifers that have themselves undergone significant reaction.

As an example of changes within the chlorite zone, the average of 5 mudstones in the 1582 to 1841m interval, near the base of the chlorite zone, has been used to estimate elemental changes relative to the parental shallow chlorite zone mudstone (Table 7e). Losses of Ca and Al, and gains of Na, Fe + Mg, and Si are indicated as feldspars and chlorite increase at the expense of illite and calcite. The open system nature of this reaction is clearly indicated by the gain in albite and chlorite from a parent that contains no Na-bearing phase and no significant Fm-bearing phase (the illite was assumed to contain 0.4Fm/10 oxygens), and the loss of calcite without the appearance of a product Ca-bearing phase. The actual reaction appears to be approximately:

A characteristic of all mudstones from the deeper chlorite zone is the removal of illite. Two individual examples of illite-free mudstone have been shown in Table 7, one with very high K-feldspar content (Table 7c) and one with a high chlorite content (Table 7f). Again Al and Ca losses, and Na gains are indicated for both examples, while the behavior of other elements varies considerably due to variations in chlorite, K-feldspar, and quartz.

Biotite Zone Mudstone

In the field interior, where a very large number of mudstone samples have been analyzed across the biotite isograd, it is very clear that the chlorite content of mudstone from the shallow biotite zone is not significantly different from that in the deeper biotite zone. Often the variability of chlorite content in the biotite zone is much greater than that in the chlorite zone, suggesting local mobility of chlorite. However, the overall reaction at the biotite isograd does not appear to be one that consumes chlorite. Chlorite does not disappear from mudstones until temperatures above 350°C. are reached. The most plausible, simplified biotite isograd reaction in the field interior is:

Within the biotite zone of the SDH, the dominant 10 angstrom layer silicate is biotite in most mudstones (Donaghe, 1987), while both K-feldspar and albite have increased significantly. An average biotite zone mudstone is shown in Table 7h. Note that calcite is still present in mudstone, even though it has been completely removed from sandstone. Calcite persists in the biotite zone mudstones of some wells in the field interior, although no calcite occurs at temperatures >350°C.

The compositional changes relative to the shallow chlorite zone mudstone have also been shown in Table 7h. Since the XRD analyses cannot reliably distinguish illite and biotite, but lumps them both

as a total 10 angstrom phase, it has been assumed that the 10 angstrom phase in these mudstones is entirely biotite. This is consistent with Donaghe's (1987, personal communication) observation that little illite is observed in biotite zone mudstones. A biotite isograd reaction for the SDH may be approximated by comparing the average biotite and deep chlorite zone analyses, and is as follows:

Unlike the interior biotite isograd, this is a chlorite-consuming reaction. The Ca losses and Fm, K, and Na gains are consistent with the general biotite isograd reaction from the field interior, but Si is gained rather than lost, and Al is lost in the SDH example. The Al loss, which is critically dependent on the assumption of no illite, is still consistent with the general Al loss from mudstones in the interior samples, and is consistent with Al loss in the other SDH examples. In the interior wells, the bulk of the Al loss is either associated with the conversion of smectite to illite or later loss of illite in clay carbonate or chlorite zones, or occurs during loss of chlorite at temperatures >250°C.. Relatively little Al loss occurs across the biotite isograd in the interior wells.

Most hand specimen descriptions of SDH core refer to the altered mudstones as having a silicified appearance. In fact, the quartz content of the altered mudstones is usually less than that of the least altered equivalents, and the main change is one of removal of illite and creation of feldspar. A single mudstone at 2164.1m in the biotite zone (Table 7g) is relatively quartz rich, but the apparent absolute gain in Si is in fact not much different from heavily feldspathized mudstone at 1985.2m. It is one of the few mudstones that have undergone any loss of Fm.

Overall Mudstone Mass Changes

Despite the lithologic variability encountered in the SDH mudstones, and the limited sample set available, several general patterns are apparent. In particular, all examples indicate Al loss in amounts of up to 25% of the original Al, while most show gains in Na and Fm, and losses of up to 100% of the original Ca. Gains of Ca are observed only in those mudstones with significant epidote, and since most mudstones are relatively low in epidote, they may be considered as overall Ca as well as Al sources in the system. Since most mudstones in the deeper chlorite and biotite zones contain more chlorite than the shallow chlorite zone parent, gains in Fm are expected in general, and are made extreme on the addition of either epidote or biotite. The Na follows albite, and since loss of albite is rare, the mudstones are typically a sink for this element. It is particularly significant that these general changes, based on very approximate calculations of a small data set, are the same as the changes determined from a much more extensive data set in the field interior.

Each XRD or XRF analysis of mudstone from the field interior is in fact the average of anywhere from 10 to 50 individual cuttings chips, and several hundred such analyses have been made in the chlor-

ite and biotite zones. It is difficult to compare the very general changes observed in cuttings with the analyses from the SDH, which represent individual rock samples and thus tend to emphasize the variability of the rocks, not their overall homogeneity. Indeed, the average of all biotite zone mudstones from the SDH does not contain as many different rock samples as does a single such analysis on cuttings from a given depth interval in an interior well. The fact that there is considerable agreement in patterns of alteration between the limited SDH modal and extensive interior XRF data sets suggests that such simplified calculations can yield useful information.

Siltstone Alteration

The extreme heterogeneity of the coarser grained sediments makes the determination of mass changes during alteration extremely difficult. Despite the fact that the XRD and thin section samples were taken within 0.1m of each other, the variability of the total layer silicate content and the patchiness of calcite and epidote cements makes comparison of the two sample sets very difficult. The mineralogical variability also makes it exceedingly difficult to define a siltstone parent. In the following discussion, a parental siltstone has been approximated by the average XRD mineralogy of 7 siltstones in the 748.8-1170.8m interval, and the possible geochemical changes calculated using this parent for series of individual siltstones using both the XRD and point counted data sets. Clearly these calculations are only rough approximations, and the limited data set available will allow only a very rough estimation of the overall changes that the siltstones have undergone.

Siltstones may be subdivided into three groups: 1) shallow layer silicate rich siltstones, at depths of <1250m, in which illite is abundant (8-35%), porosities high (10-24%), calcite is present in moderate amounts (6-13%), and epidote is present in trace quantities; 2) deeper chlorite zone siltstones which are illite free and K-feldspar rich, and have highly variable amounts of calcite (0-22%) and epidote (0-20%), but moderate porosity (10-17%); and 3) siltstones from the biotite zone that are calcite free, contain variable amounts of biotite, chlorite, K-feldspar, and pore space, and an extreme range of epidote (1 to 70%). Examples of mass changes have been given in Table 8, relative to a layer silicate-rich siltstone parent from group 1.

Within the group 1 siltstones in the shallow chlorite zone, several exceedingly illite rich and K-feldspar poor siltstones were observed, and an average of 3 of these from 1222.1 to 1233.8 m depth is given in Table 8b. Very few siltstones have been noted like these in the interior of the geothermal field, and where such rocks have been observed, the removal of K-feldspar is definitely due to alteration under biotite zone conditions. Since these illite-rich samples occur in the shallow chlorite zone, it is possible that they are due to stratigraphic variations and not alteration. A reaction origin would require an open system reaction of K-feldspar to Illite in which significant Al was consumed and Si produced, and could represent an extreme example of illitization of detrital alkali feldspar.

The most prevalent mineralogical change in the chlorite zone is the decrease in illite and increase in K-feldspar at depths >1250m. While in detail illite completely disappears while calcite remains

TABLE 8 Mass Changes of Altered Chlorite Zone Siltstones.

	Parent a	b	c	d	e	f	g
	(7)	(3)	1317.8	1293.3	1984.2	1415.3	1420.4
Pore	12.0	11.7	11.0	13.0	6.0	17.0	14.0
Qtz	23.0	20.1	23.9	16.8	11.1	17.3	26.0
Ab	17.8	17.8	22.7	18.7	23.2	16.1	0
Ksp	8.6	1.0	20.6	35.1	41.3	25.6	20.2
Ill	16.6	33.9	0	0	0	0	0
Chl	12.1	10.7	11.4	8.1	15.7	12.7	19.7
Calc	8.8	8.7	8.9	7.1	2.7	0	0
Py	0.5	3.1	1.5	1.2	0	1.3	0
Ep	0	0	0	0	0	10.0	19.9
Ah	0.6	0.7	0	0	0	0	0

Change in mMols relative to 100cc parent siltstone

Si	-	-247	+102	+522	+310	+61	+129
Al	-	+149	-143	+6	+108	-2	-10
Na	-	-81	+48	+9	+54	-17	-177
K	-	+47	+2	+146	+207	+52	-2
Fm	-	+108	-21	+77	+18	+73	+193
Ca	-	0	-11	-57	-178	-107	+33
CO ₂	-	-2	+2	-46	-238	-238	-238
H ₂ O	-	+98	-129	-41	-49	-69	+98

See Table 7 for explanation.

high and significant epidote has yet to form, when viewed over a greater depth range the basic closed system reaction is the same calcite + illite to epidote + K-feldspar reaction that was operative in the mudstones at this depth. Several individual examples have been given in Table 8. Siltstones c, d, and e in the table represent a sequence of examples in which illite has been completely removed and K-feldspar formed in increasing amounts, while calcite, chlorite, and albite have changed very little. In a general way these samples demonstrate that, if chlorite and albite do not change significantly, the K-feldspar must increase to >35% before compensation is made for the large amount of Al lost on the disappearance of illite and the siltstones can gain in Al. Thus moderate feldspathization can produce loss of Al, while extreme feldspathization results in gains in Al as well as K and Si.

The siltstone at 1984.2m (e in table), at the biotite isograd, also demonstrates a second alteration trend that is more typical of siltstones from the biotite zone. In this case quartz is clearly consumed during extreme feldspathization just as it is consumed in the biotite zone during extreme epidotization.

Two examples of deep chlorite zone siltstones in which both illite and calcite have been consumed, and epidote produced, are given in Table 8f and g. The main difference between the two siltstones is that in f albite has remained high, while in g it has been completely removed. Of the two, f is mineralogically the most typical of deep chlorite zone siltstones from the field interior, and shows no Al change from the chosen shallow chlorite zone parent. The albite depleted siltstone (g) is unusual relative to the interior of the field, but is also observed in sandstones from the SDH. However, variations in the albite/K-feldspar ratio of all lithologies in the field interior clearly indicate that, during alteration, a simple feldspar alkali exchange reaction was operative in both directions at various locations and temperatures. The result is a complex pattern of albite/K-feldspar ratios in the deep chlorite and biotite zones that is different from well to well and presumably reflects a combination of fluid compositional variations and varying approaches to complete equilibration.

There are very few XRD analyses of siltstones from the biotite zone, and these are shown in Table 9b, c, and d. The first example (b) is representative of those few siltstones in which only small amounts of epidote have formed, and the main layer silicate phase is chlorite, not biotite. Since both feldspars are enriched, significant Al has been gained along with the alkalis. Siltstones c and d in the table contain both biotite and epidote, but reduced K-feldspar, while chlorite is highly variable. A comparison of the three siltstones indicates that K-feldspar is a reactant in the biotite-forming reaction, but the role of chlorite is clearly ambiguous as it is in the mudstones. The high chlorite content of c implies that it is a product of the biotite forming reaction, while the very low amount in d implies it is a reactant. It is very clear that the actual biotite forming reactions are open system reactions in which a significant flux of elements occurs during reaction. Note, however, that both biotite bearing siltstones have gained in Al and Fm, but lost significant K.

Because of the unavailability of XRD analyses of highly epidotized siltstones, and the prevalence of such rocks in thin section, three

TABLE 9 Mass Changes of Altered Biotite Zone Siltstones

	Parent a	b	c	d	e 45% Ep +Bio,Chl	f 50% Ep	g 70% Ep
	(7)	2060.5	1984.9	2483.1			
Pore	12.0	8.0	6.0	4.0	10	20	15
Qtz	23.0	12.7	21.9	12.9	10	10	5
Ab	17.8	27.3	16.7	22.4	10	10	5
Ksp	8.6	32.0	6.6	8.3	5	10	5
Ill	16.6	0	0	0	0	0	0
Chl	12.1	12.7	22.1	2.7	10	0	0
Calc	8.8	0	0	0	0	0	0
Py	0.5	2.5	2.5	0	0	0	0
Ep	0	5.0	10.1	14.7	45	50	70
Ah	0.6	0	0	0	0	0	0
Bio	0	0	16.6	31.4	10	0	0
Act	0	0	0	3.5	0	0	0

Change in mMols relative to 100cc parent siltstone

Si	-	+293	-126	+228	-140	-227	-312
Al	-	+100	+16	+63	+271	+230	+454
Na	-	+95	-10	+45	-79	-79	-129
K	-	+115	-136	-119	-156	-109	-159
Fm	-	+88	+675	+491	+416	+7	+150
Ca	-	-179	-107	-17	+395	+467	+753
CO ₂	-	-238	-238	-238	-238	-238	-238
H ₂ O	-	-87	+220	-26	-74	-166	-94

See Table 7 for explanation.

examples of epidotized siltstones have been reconstructed by combining the point counted and XRD data. One (e) contains biotite and chlorite in typical amounts, as well as increased porosity and high epidote contents, while the other two (f,g) are clean, layer silicate-free siltstones with varying amounts of epidote. Comparison with the parental siltstone indicates gains of up to 50% of the original Al and a possible doubling of Ca, combined with large losses of Si, Na, and K, and gains in Fm.

If the elemental changes of Tables 8 and 9 are compared, it is clear that, for the most part, the siltstones gain in Al during alterations as long as a moderate amount of epidote is present. Where massive epidotization has occurred, the addition of massive amounts of Al are required if the assumption of no compaction is even approximately correct. Clearly the combination of feldspar and epidote formation requires far more Al than can be supplied by any preexisting illite. In general, chlorite zone siltstones represent a moderate sink for Al, while the dominant epidote-rich siltstones of the biotite zone require major additions of Al. In addition, while most siltstones lose Ca, in zones of epidotization significant Ca is regained.

The patterns of change of the other elements are more complex. In very broad terms Si is gained by the deeper chlorite zone siltstones, but lost in the biotite zone. K is gained as long as the epidote content stays under about 15%, but for more epidote-rich siltstones K is lost. Almost all siltstones gain Fe + Mg, with both being enriched in approximately equal amounts as long as biotite and chlorite are dominant, but with Fe enrichment and Mg loss as epidote becomes dominant in the biotite zone. Na is dependent only on the albite content of the siltstone, and is gained except where epidotization has reduced the feldspar content significantly.

Siltstone vs Mudstone Alteration

The dominant lithologies penetrated by the SDH are mudstone and siltstone, with the former dominating at depths >1800m. The calculations above, while very simplified, provide a general idea of the flux of elements both between fluid and rock, and, via the fluid, from rock to rock. In particular, all mudstones lost Al during alteration in the deeper chlorite and shallow biotite zones, while the siltstones in general gained Al. In the deeper chlorite zone about 15% of the original Al is lost from mudstone, while in the shallow biotite zone Al losses of almost 25% are common. Calculations in the interior field, based on XRF analyses and immobile element assumptions, indicate even greater Al losses from mudstone in the deeper biotite zone where chlorite finally disappears. At the same time, siltstones from the deeper chlorite zone have gained up to 18% of the original Al, while gains of up to 56% of the original Al are possible in the extremely epidotized siltstones of the biotite zone. The very limited sampling of biotite zone siltstones does not allow a realistic average Al gain to be made, but it is clear from Table 9 that an overall 15 - 20% gain would be quite reasonable. Despite the simplifications in the calculations, a significant transfer of Al from mudstone to siltstone is apparent during alteration in the deeper chlorite and biotite zones at temperatures above about 275°C.

The calculations also indicate that most mudstones and siltstones lose Ca except where epidotization is extreme in the siltstones of the

biotite zone, while both sets of rocks gain Fe and Mg under most conditions. Again investigations in the field interior indicate that the lithologically dominant mudstones do not lose significant Fe and Mg until chlorite is lost in the deeper biotite zone. This suggests that the source for Fe and Mg in the chlorite and shallow biotite zones may be upward moving fluids that gained these same elements in the deeper biotite zone not penetrated in the SDH. With the exception of the shallow, extremely feldspathized mudstones, most mudstones lose small amounts of K, as do siltstones from the biotite zone, while siltstones from the chlorite zone typically gain K. Again a flux is suggested from mudstone to siltstone, or via upward moving fluids which pass through biotite zone rocks.

It is clear from these very approximate calculations that significant elemental fluxes occur between lithologies in this geothermal/hydrothermal system. It is also abundantly clear that Al may not be considered immobile in this system, a conclusion reached using an independent XRF data base in the interior parts of the geothermal field. Open system reactions are the rule in this system, and in most cases, it is not possible to write the typical closed system (except to H_2O and CO_2) reactions used in traditional metamorphic petrology. Even the least permeable mudstones are dominated by open system reactions in this geothermal system, and there is no reason to suspect that, in regional zeolite or greenschist facies metamorphism, similar open system reactions are not also important despite the apparent impermeability of the rocks.

The majority of mudstones and siltstones have undergone significant loss of volatiles, in particular CO_2 . Indeed, the complete decarbonation of siltstone and partial decarbonation of mudstone in the biotite zone everywhere in the geothermal system represents a major addition of CO_2 to the fluid phase, and is presumably the ultimate source of that gas in the former commercial carbon dioxide field located just to the north of the SDH. The localization of gas emissions at the northeast end of the geothermal system requires a pore/fracture plumbing system that is capable of moving very large amounts of CO_2 laterally from the center of the field and then upward, presumably in fractures, through both the more mudstone-rich fluvial-deltaic rocks in this part of the geothermal system, and the overlying poorly consolidated lacustrine mud-dominated section. This whole process is presumably related to the distribution of seismicity, deformation, and fracture formation in this tectonically active sedimentary section.

In addition to CO_2 loss, most rocks also show a loss of H_2O in moderate amounts. The only rocks that have gained in water are those in which chlorite has increased significantly relative to the parent rock, and such rocks, though sporadically present, are clearly in a minority.

Sandstone Alteration

Sandstone is a relatively minor lithology in the SDH, and as a result is poorly sampled throughout the well. The mineralogical changes observed in thin section have already been documented in the mineralogy/petrology section. Since no XRD analyses are available for sandstones from the biotite zone, and relatively few such analyses are available from the chlorite zone, it is difficult to obtain much sense

TABLE 10 Mass Changes of Altered Sandstone

	Parent a	b	c	d	e	f Ep+ Act
	(5)	1308.8	1425.9	1419.8	1837.7	
Pore	21.4	10.0	11.0	6.0	4.0	5
Qtz	38.5	62.9	40.1	45.5	26.4	10
Ab	12.5	0	0	0	19.6	18
Ksp	16.7	21.0	28.1	16.1	4.9	5
Ill	1.4	0	0	0	0	0
Calc	0.5	0.6	0	0	22.2	0
Py	0.2	1.2	2.6	0	0.5	0
Ep	0	0	14.9	28.4	0	49
Act	0	0	0	0	0	13

Change in mMols/100cc parent sandstone

Si	-	+733	+244	+434	-512	-155
Al	-	-152	+122	+209	+60	+533
Na	-	-125	-125	-125	+71	+55
K	-	+33	+103	-16	-127	-126
Fm	-	-64	+68	+87	+339	+370
Ca	-	+3	+190	+394	+588	+786
CO ₂	-	+3	-14	-14	+588	-14
H ₂ O	-	-98	-65	+8	+508	+46

See Table 7 for explanation.

of the overall changes that these rocks underwent during alteration. In general, the sandstones change from open porous rocks with moderate chlorite contents and small amounts of illite and calcite to calcite and illite free rocks of moderate porosity that contain varying amounts of epidote and minor amounts of biotite and actinolite. In addition, quartz and feldspar overgrowths and pore-filling aggregates account for a significant part of the porosity reduction observed during alteration.

An average of 5 sandstones from the shallow chlorite zone has been taken as an approximate parent sandstone in Table 10a, and elemental changes have been calculated for a small number of individual sandstones at greater depth. The first sandstone (b in Table 10) is a highly silicified, albite-free example that is representative of both chlorite or biotite zone sandstones in which patchily distributed quartz overgrowths are extensive but other alteration minerals are not observed. The calculations indicate a loss of most elements except Si, which as expected shows massive gains.

Sandstones c and d in the table are representative of a very large number of sandstones of both the biotite and chlorite zones in which the dominant alteration effects include quartz and feldspar overgrowths and the appearance of various amounts of epidote that has both filled pore space and replaced feldspar. As noted in the siltstone discussion above, such albite-free rocks are not commonly observed in other parts of the geothermal system, and it is not clear how extensive such sandstones are in the SDH. The calculations clearly show significant gains in Si, Al, Fm, and Ca relative to the parent sandstone. Because the illite content of the parental sandstone is so low, only moderate amounts of epidote need be added before any Al losses due to illite removal are overcome, and a net gain in Al is allowed. The fact that albite is removed has relatively little effect on the Al balance due to the higher Al/mol content of epidote relative to feldspar. While clearly limited, these calculations support those of the siltstones, and indicated that all the coarser clastic rocks are sinks of Al that was transferred from mudstone during alteration.

Sample e is representative of a small number of chlorite zone sandstones that are epidote free, and contain unusually high amounts of chlorite and calcite. Extreme Si losses and gains of Ca and volatiles are indicated. The final sandstone (f) has been reconstructed from the mode of a very epidote and actinolite rich sandstone, using XRD analyses on siltstones at similar depths to approximate the feldspar and quartz contents since these minerals were lumped in the point counts. It is not a commonly occurring rock type, but is representative of actinolite-rich sandstones found everywhere in the biotite zone of the geothermal system. Again the addition of massive amounts of Al, Fm, and Ca are indicated.

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