DOE/ER/13407--T1

DE87 009445

FINAL REPORT

DOE/BES CONTRACT DE-FG01-85ER13407

"CORES FROM THE SALTON SEA SCIENTIFIC DRILLING PROGRAM: METAMORPHIC
REACTION PROGRESS AS A FUNCTION OF CHEMICAL AND THERMAL ENVIRONMENT"

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Date: May 13, 1987

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The intent of this study was to investigate the downhole progressive metamorphism at the Salton Sea site by monitoring and evaluating discontinuous and continuous metamorphic reactions. The main emphasis was placed on: (1) the addition of petrographic, geochemical, and mineralogical data to the Salton Sea data base; (2) determination of downhole reactions; (3) evaluation of the progress of individual continuous reaction (ϵ) and the overall reaction progress (ϵ_T) during the transition from one metamorphic zone to the next; and (4) evaluation and correlation of mineral reactions and reaction progress with mineral phase and organic material geothermometry. To these ends, thirty-three samples (Table 1) from the Salton Sea core were analyzed for: (1) quantitative modal mineralogy using the X-ray diffraction reference intensity method (RIM), (2) 30 major and trace elements in the whole rock and (3) mineral chemistry and structural state. In addition, a subset of these samples were used for temperature determinations using vitrinite reflectivity.

Table 1. Depth of Samples Used in This Study (in feet)

1561.60	4678.00	6880.80	8395.70	9907-9912 (2)
2011.80	5575.20	7306.50	8802.60	
2971.00	5575.50	7548.30	9249.30	
3014.05 (2)	6040.00	7550.20	9249.60	
3146.90	6510.00	7729.35	9474.00 (3)	
4244.40	6510.25	7730.00	9694.20	
4244.50	6511.00	8138.50	9649.30	

Quantitative statistically relevant modal mineralogy of the core samples were determined utilizing a reference intensity (RIM) multi-component X-ray diffraction analysis. Preferred orientation and absorption errors were minimized by reducing the particle size of the sample material to values in the 5-15 micron diameter range and by

suspending the samples as an aerosol in an aspirator jar and collecting the aerosol particles on an amorphous fiber filter substrate. X-ray analysis was then accomplished by scanning the thin aerosol layer directly on the substrate and correcting the intensities for transparency and matrix absorption. The corrected intensities were then reduced to weight fractions for each component of the sample according to the Chung equation (Chung, 1974).

Based upon the XRD-RIM, six mineral assemblages have been identified in these samples: (A) CHLORITE + CALCITE + Quartz + Plagioclase $\pm$ K-feldspar $\pm$ Illite (1561.6' - 8395.7'), (B) CHLORITE + Quartz + Plagioclase + K-feldspar (3014.05' - 6510.0'), (C) CHLORITE + EPIDOTE + Quartz $\pm$ Plagioclase $\pm$ Calcite $\pm$ K-feldspar $\pm$ Illite (2971.0' - 9694.2'), (D) CHLORITE + BIOTITE $\pm$ Calcite + Quartz + Plagioclase + K-feldspar (8858.3' - 9249.3'), (E) EPIDOTE + Quartz $\pm$ Plagioclase (7550.2' - 9694.3') and (F) EPIDOTE + "ACTINOLITE" + Quartz $\pm$ Biotite $\pm$ Chlorite $\pm$ Plagioclase $\pm$ K-feldspar $\pm$ Anhydrite (9249.6' - 9912.0'). These mineral assemblages allow identification of prograde "metamorphic" zones of: (1) CHLORITE zone, (2) BIOTITE zone, and (3) ACTINOLITE zone.

Sample splits were analyzed for major and trace elements using XRF. Elemental analyses included SiO_2 , TiO_2 , Al_2O_3 , Fe_2O_3 (total Fe), MnO, MgO, CaO, Na_2O , K_2O , SO_3 , Cl, As, Ba, Br, Ce, Cr, Cu, Ga, La, Mo, Nb, Ni, Pb, Rb, Sr, U, V, Y, Zn, and Zr. The samples displayed a wide variation in bulk composition. As an example: SiO_2 = 36.2 to 81.2 wt.%, Al_2O_3 = 5.1 to 17.1 wt.%; CaO = 1.2 to 21.1 wt.%; $\text{FeO}/(\text{FeO}+\text{MgO})$ wt. ratio = 0.48 to 0.98, SO_3 <0.07 to 10.4 wt.%; Cl = 0.02 to 0.91 wt.%, Br <1 ppm to 7.5 ppm; and Cu = 6.8 to 160 ppm.

Combination of XRD-RIM modal mineralogy with whole rock chemistry has been used to compare metamorphism of similar bulk compositions and metamorphic mineral assemblages in different bulk composition. Two examples follow:

Bulk Composition 1: $\text{SiO}_2 = 55 - 57.5\%$, $\text{Al}_2\text{O}_3 = 16.5\% - 17.4\%$; $\text{CaO} = 4.60 - 5.88\%$; $\text{K}_2\text{O} = 3.1 - 4.1\%$

Modes in wt. %:

	1561.6	7548.3	8395.7	9249.30
Biotite	--	--	--	5.6
Illite	48.9	26.4	17.7	--
Chlorite	14.4	18.6	7.8	4.7
Albite	2.3	26.0	26.0	38.1
Quartz	22.0	25.1	21.8	14.0
K-feldspar	2.2	--	21.8	36.3
Calcite	10.0	3.6	4.5	--

Bulk Composition 2: $\text{SiO}_2 = 59 - 63.9\%$; $\text{Al}_2\text{O}_3 = 13.9 - 14.5\%$; $\text{CaO} = 4.00 - 4.10\%$; $\text{K}_2\text{O} = 4.6\% - 6.2\%$

Modes in wt. %:

	6040.00	9907-9912 Shale
Chlorite	13.8	0.6
Biotite	--	5.8
Actinolite	--	5.0
Epidote	--	4.5
Albite	21.3	28.0
Quartz	21.3	27.5
K-feldspar	38.3	28.6
Calcite	5.1	--

Where grain size permitted, analyses of chlorite, biotite, epidote, "actinolite", and feldspar were determined by electron microprobe. Down hole analyses of these minerals are illustrated in Figures 1 to 5. In addition to the chemical composition of mineral phase, the structural state of K-feldspar was also determined (Figure 6). In the K-feldspar, the Si-Al ordering generally decreased with increasing depth.

The preliminary data from this study was initially reported at the SSDP progress report symposium at Palm Springs, California. In addition, two abstracts have been submitted and accepted for the spring AGU Salton Sea Symposium (Appendix I). One oral presentation will be given at this meeting. We also intend on submitting two full length manuscripts to the Salton Sea volume to be published in the Journal of Geophysical Research.

References

- Chung, F., 1974, Quantitative interpretation of x-ray diffraction patterns of mixtures II. Adiabatic principle of x-ray diffraction analysis of mixtures. J. Appl. Cryst., 7, 526-531.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

K-FELDSPAR STRUCTURAL STATE

Appendix 1

Progress of Mineral Reactions: Variations in the Modal Mineralogy, Mineral Chemistry and Bulk Chemistry of the SSSDP Core

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XRD-RIM modes, whole rock chemistry, and mineral chemistry were determined on thirty-three samples from the SSSDP core; vitrinite reflectance temperatures were determined on a subset of these samples. These samples display a wide variation in grain size (shale to sandstone), bulk composition [$\text{SiO}_2 = 36.2 - 81.2$, $\text{Al}_2\text{O}_3 = 5.1 - 17.1$, $\text{CaO} = 1.2 - 21.1$ wt.% and $\text{FeO}/(\text{FeO}+\text{MgO})$ wt. ratio = $0.48 - 0.98$] and mineral assemblage. Six mineral assemblages have been identified in these samples: (A) CHLORITE + CALCITE + quartz + plagioclase $\pm$ K-feldspar $\pm$ illite (1561.6'-8395.7'), (B) CHLORITE + quartz + plagioclase + K-feldspar (3014.05' - 6510.0'), (C) CHLORITE + EPIDOTE + quartz $\pm$ plagioclase $\pm$ calcite $\pm$ K-feldspar $\pm$ illite (2971.0'-9694.2'), (D) CHLORITE + BIOTITE $\pm$ calcite + quartz + plagioclase + K-feldspar (8858.3'-9249.3'), (E) EPIDOTE + quartz $\pm$ plagioclase (7550.2'-9694.3') and (F) EPIDOTE + "ACTINOLITE" + quartz $\pm$ biotite $\pm$ chlorite $\pm$ albite $\pm$ K-feldspar $\pm$ anhydrite (9249.6'-9912.0'). Quantitative modal mineralogy and whole rock chemistry can be utilized to complement mineral chemistry in evaluating progressive metamorphism at the SSSDP site. As an example, the prograde reactions represented by assemblages (A), (B) and (C) are characterized by (1) increasing Si-Al disorder in K-feldspars with depth; (2) $\text{Fe}/(\text{Fe}+\text{Mg})$ in chlorite related to bulk rock $\text{Fe}/(\text{Fe}+\text{Mg})$; (3) $\text{Fe}/(\text{Fe}+\text{Al})$ in epidote decreases with depth, and within individual samples increases toward vein systems; (4) the proportion of illite to K-feldspar in rocks with the same bulk composition varies substantially but irregularly downhole; and (5) the progress of the "epidote-in reactions" varies irregularly downhole but can be monitored by XRD-RIM determined weight proportions of epidote, calcite and anhydrite.

Appendix 1 (continued)

X-Ray Reference Intensity and X-Ray Fluorescence Analysis
of Salton Sea Core

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Recently developed quantitative x-ray diffraction (XRD) and x-ray transmission (XRT) procedures have been combined with x-ray fluorescence (XRF) and atomic absorption (AA) to completely characterize the mineralogy and chemistry of 33 core samples obtained from the Salton Sea Scientific Drilling Program well. The XRD-reference intensity method (RIM) for determining quantitative modes includes the creation of an aerosol from a finely pulverized sample, followed by collection of randomly oriented particles on a glass fiber substrate. The analysis requires integrated intensities corrected for matrix and transparency of the collected aerosol layer. Major mineral components in the SSSDP samples include quartz, orthoclase, plagioclase, chlorite, epidote, illite, and calcite, with minor pyrite, phlogopite, halite, anhydrite, and actinolite. Glycol treatment of the samples demonstrated a lack of significant amounts of smectite, and illite was observed to be the dominant dioctahedral phyllosilicate. Mineral compositions determined by electron microprobe were combined with the XRD modes to yield calculated bulk rock compositions. A comparison between XRD computed chemistry and observed XRF chemistry was used to determine which (if any) reference constants required significant adjustment. Such adjustments for quartz and illite were required to accommodate differences between the XRD and XRF results. Agreement between XRD and XRF oxide values was generally good, although the final XRD set still underpredicted SiO_2 following reference constant adjustment. Mass absorption coefficients determined for all samples by XRT compared well with values computed from the final set of reduced XRD oxides and measured XRF oxides.