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December 28, 1988

Dr. Daniel Carrier
Unocal Geothermal Division
Unocal Corporation
3576 Unocal Place
Santa Rosa, California 95406

Dear Dr. Carrier,

The x-ray diffraction analysis and reconnaissance petrographic analysis of cuttings from the "17"-series group are complete and appended to this letter. The results are further interpreted in the text that follows.

Rock type and mineralogy-

The "17"-series group is predominantly andesite and dacite. Compositional and textural variations of the andesite are orthopyroxene or clinopyroxene andesites, porphyritic or aphyric andesites, amygdaloidal basaltic andesites, microdiabase and meta-andesite and meta-diabase. Dacitic composition rocks include the varieties, dacite and rhyo-dacite, both porphyritic and aphyric. The lowest part of this group is granodiorite, which may or may not be genetically related to the overlying dacite.

Samples 17-1 through 17-3 exhibit relict perlitic and other devitrification textures preserved in cristobalite which has partially altered to aragonite. Most of the original mafic content of the groundmass has altered to hematite. Aragonite, smectite and traces of analcime are present as amygdule fillings. Hematite has also replaced the aragonite in some of the amygdules. Orthopyroxene phenocrysts are also common in the more phyric andesites. This interval of rocks seems to represent an originally glassy andesite flow.

Samples 17-4 through 17-6 are predominately dacite. Granophyric and spherulitic texture is well developed. Sieve-textured feldspar phenocrysts are also common in this interval. Sample 17-6 is partially silicified and partially granophyric. It could represent the originally glassy border of a shallow dacite intrusive.

Samples 17-7 through 17-16 are predominately flow-banded andesites and clinopyroxene andesites. Rare orthopyroxene phenocrysts subophitically enclose plagioclase phenocrysts in some chips. Microdiabase is common below sample 17-12 where it probably represents a slightly coarser-crystalline variant of the andesites. This interval is characterized by the alteration minerals: epidote, leucoxene and chlorite-rich chlorite-smectite. Subordinate anhydrite and wairakite are also present. The leucoxene outlines amygdules where it probably replaced primary magnetite. Quartz veins are common in samples 17-14 through 17-16.

Samples 17-17 through 17-20 are mostly porphyritic andesites and samples 17-22 and 17-25 are coarser-grained granodiorites. The granodiorites contain primary phenocrysts of hornblende and biotite. Sample 17-19 contains clasts of sandstone (now hornfels) with grains of rounded quartz that exhibit overgrowths. It may be possible that this granophyric-textured sample represents a basal flow which has picked up some grains of country rock during its deposition. Alternatively, if this dacite represents a shallow intrusive, the hornfels may be xenoliths.

Below sample 17-20 and above the granodiorite of sample 17-25, there is a zone of contact metamorphism. Granoblastic recrystallization of the original micro-diorite is locally evident in sample 17-24. The rocks is this zone are better termed meta-andesite and meta-diabase, metamorphic equivalents of the igneous rocks. Samples 17-22 and 17-25 probably represent the granodiorite intrusive responsible for the metamorphism.

Minor amounts of actinolite are present in samples 17-12 through 17-16 where it is associated with epidote and possibly crosscut by chorite-quartz veins. In other chips, the formation of epidote seems to post-date chlorite formation. The iron content of the tremolite-actinolite increases with depth, at the depth of sample 17-20 it appears pleochroic and green in plane light.

Some of the amphibole in samples 17-17 and 17-22 may be primary hornblende but most is altered to actinolite. In samples 17-18 and 17-19, the actinolite does not appear to have altered from primary hornblende and occurs in irregular veins. By the depth of sample 17-20, veins and nodules of actinolite and fine-grained veins of biotite-actinolite-talc become common. Sample 17-25 contains both primary hornblende, and primary and secondary biotite.

Most of clinopyroxene in the zone of contact metamorphism (samples 17-21, 17-23 and 17-24) is probably metamorphic in origin. It appears polygonal and equigranular, and is enclosed in potassium feldspar, triple-junction quartz, or more rarely, biotite in an incipient granoblastic texture. Although some of the clinopyroxene may be primary, it does not occur in the usual interstitial manner of igneous pyroxene.

The presence of secondary biotite in samples from the bottom of this well is also associated with thermal metamorphism of the granodiorite; the biotite occurs in fine-grained aggregates or poorly defined veinlets. However, the overlying volcanic flow rocks contain well-defined crosscutting veins of biotite-actinolite-talc that are more positively hydrothermal in origin.

Alteration zoning-

The rocks penetrated by this well clearly show well-defined mineralogic zoning which is related to increased temperatures with depth. The problem is distinguishing hydrothermal alteration from contact metamorphism.

The origin of high-level smectite, quartz and calcite, and mid-level epidote, wairakite and prehnite is almost certainly hydrothermal because these minerals occur in veinlets (and in some amygules). Some of the deeper biotite, actinolite (and rare clinopyroxene?) also occur in veins and are probably hydrothermal. However, much of the biotite and especially clinopyroxene in the zone of metamorphism is metamorphic, the rock is trying to become a hornfels.

The vein assemblages do provide information about the temperatures of the hydrothermal fluids from which some of the secondary phases were deposited. Epidote tends to form above 240° C; prehnite above 215° C; wairakite above 210° C; actinolite above 280° C; and biotite above 220° C (more commonly above 300° C) (e.g. Browne, 1978, 1984; Hulen and Nielson, 1986).

The layer silicate mineralogy of this well also reflects zoning related to temperature. Samples 17-1 through 17-4 contain 10% to 20% smectite. The air-dried basal spacing of the smectite at 14A suggests that calcium and/or magnesium are the principal interlayer cations. Because these smectites are high-level and occur in rocks that contain analcime rather than wairakite, they probably formed at low temperatures, below 160°C (Hulen and Nielson, 1986).

Samples 17-5 through 17-15 contain discrete chlorite and some mixed-layer chlorite-smectite. Some samples in this interval also contain mixed-layer illite-smectite. The amount of illite interlayers in the illite-smectite is about 70-90%. These low-expandability mixed-layer clays usually form between 175°C and 220°C (Browne, 1984) from precursor smectites, so they could have been generated during incipient to low-grade metamorphism as well as subsequent hydrothermal alteration.

Below sample 17-16, the chlorites are either discrete forms or they occur in mixed-layer chlorite-smectite. This variety of chlorite-smectite is ordered and contains about 60 to 90% smectite as indicated by a superlattice peak at about 29A (in air-dried samples). Mixed-layer chlorite-smectites are stable between 200°C and 270°C (Browne, 1984), a temperature also permitting a low-grade metamorphic origin.

Samples 17-19 through 17-25 contain two varieties of mixed-layer chlorite-smectite, one with about 50% chlorite and the other with about 80% chlorite interlayers. The occurrence of the unordered, 50% chlorite variety with clinopyroxene, epidote and biotite, may indicate a cooling trend at depth since the higher temperature phases were formed.

Discussion-

Traces of the high-temperature alteration phases, actinolite and epidote, are present in a few fragments from the highest levels in this well (samples 17-1 and 17-2). The unusual occurrence of these high-temperature alteration phases in lower-temperature argillically-altered rocks may possibly represent lithic fragments of altered rock in dacite dikes at this level.

Veins containing intergrown calcite and quartz are common in sample 17-4. Calcite is replacing both wairakite and epidote in sample 17-7. Both these occurrences of calcite suggest that boiling (and CO^2 exsolution) has occurred at these levels at some time.

Below the depth of samples 17-16 and 17-17, a change in alteration occurs. Samples 17-14 and 17-16 are partially silicified. Samples 17-17 to 17-24 contain less epidote, anhydrite and leucoxene, and more actinolite, biotite, talc and ordered chlorite-smectite as alteration minerals. Perhaps the change in mineralogy reflects the change from a vapor-dominated upper zone to a water-dominated reservoir zone.

To conclude, the alteration in this well is zoned as a result of both metamorphic and hydrothermal processes. A shallow argillic zone contains abundant smectite, illite-smectite and hematite, possibly as a result of hydrothermal alteration. Cristobalite occurs as a devitrification product and aragonite, a low temperature alteration of the glass. The andesitic flow rocks in this interval may be locally cut by dacite dikes. Underneath this zone is a hydrothermal, propylitically-altered zone containing abundant epidote, chlorite and wairakite that probably formed at moderately high temperatures. Subordinate amounts of anhydrite, prehnite and illite-smectite are also present as vein-forming minerals. A silicified interval at the base of this zone may mark the transition into the lower, higher-temperature, more potassic, alteration zone. This interval is characterized by hydrothermal veins of actinolite-biotite-talc. The hydrothermal alteration in this zone seems to be superimposed on an older contact metamorphic zone characterized by biotite and clinopyroxene, which may represent a pyroxene-hornfels facies of metamorphism. The chlorite-poor chlorite-smectite in this zone may be the result of a much later, and cooler, hydrothermal system. Intrusive rocks are penetrated in the lowest part of the well. Some of the secondary biotite in the granodiorite appears to be of metamorphic rather than hydrothermal origin. This intrusive body may represent the source of thermal metamorphism.

Thanks for the opportunity to work with these interesting cuttings. I realize that this interpretation of the origin of the clinopyroxene at the bottom of the well differs from yours. However, Jeff Hulen and I both looked at the thin-sections and we are fairly confident that most of this pyroxene is neither igneous nor hydrothermal. If you care to discuss this further or if you have any more questions about the x-ray or petrographic signatures of these rocks, please call.

Sincerely,

Susan Lutz

Susan Lutz
Manager,
X-ray Diffraction Laboratory

References

Browne, P.R.L., 1978, Hydrothermal alteration in active geothermal fields: Ann. Rev. Earth Planet. Sci., v. 6, p 229-250.

Browne, P.R.L., 1984, Lectures on geothermal geology and petrology: United Nations Univ., Geoth. Training Prog., Rept. 1984-2, 92 p.

Hulen, J.B. and Nielson, D.L., 1986, Hydrothermal alteration in the Baca geothermal system, Redondo dome, Valles caldera, New Mexico: J. Geophs. Res., v. 91, p. 1897-1886.

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17- SERIES

BULK XRD SAMPLE NO.	CRISTOBALITE	QUARTZ	PLAGIOCLASE	K-FELDSPAR	CALCITE / ARAGONITE	CLINOPYXN / ORTHOPYXN	ACTINOLITE / HORNBLENDE	EPIDOTE	SPHENE & LEUCOXENE UNDIV.	MAGNETITE & ILMENITE UNDIV.	HEMATITE	PYRITE	ANHYDRITE	WAIRAKITE / ANALCIME	SMECTITE	CHLORITE & CHLORITE-SMECT UNDIV.	ILLITE & ILLITE-SMECT UNDIV.	BIOTITE	TALC		AMORPHOUS OR BELOW DETECT.	OTHER	
17-1	24	1	33	7	/TR	1/1		TR	5	1	12			/TR	12							3	← GOETHITE
17-2		TR	31	2?	/1	8/TR		TR	11	4	4			/TR	17						•22		• MOSTLY GLASS
17-3		TR	26		/3	1/TR			9	5	7			/TR	22						•27		• MOSTLY GLASS
17-4	25	6	15	26	1	TR			5	1	2	3			8	1					7	TR	← LAUMONTITE ? IN QTZ VEIN
17-5	5?	16	30	10	2/1			TR	13	TR		4			4	3					12		
17-6		22	26	15	2			1	6		1	3		TR	4	1	12				7		
17-7		10	26	5	12			8	11		2	TR		7		11	2				6		
17-8		13	25	13	3	7		6	7	5	3			2		4		TR			12		
17-9		10	23	10	1			26	9		2	3	TR	2	1	12						1	← PREHNITE
17-10		15	31	15	1	1	TR	13	7	2		3		4		5	2					1	← PREHNITE
17-11		8	26	4		1		16	12	1	2	3	1	3		11	1				11		
17-12		6	27	8	TR	11	3	8	11	4	2	1	TR	1		7					11		
17-13		12	28	9	TR	13	3.	8	9	5	1	TR				5			TR		6	1	← DRILL STEEL
17-14		8	24	14		1?	2	26	9		TR	TR	TR			5					10	TR	← DRILL STEEL
17-15		11	23	4			5	23	13	1		TR				7					13		
17-16		11	22	6			5	17	10	2	TR	1	TR			12					14		
17-17		4	35	5			12	9	7	8		1				8					11		
17-18		8	22	8			3	18	11	4		TR				16					10		
17-19		24	26	17			1	3	*11	1		TR				7					10		* ? VERY FINE-GRAINED
17-20		2	35	4		TR	14	2	5	11		1				8		3	1		14		
17-21		1	38	3		15	4	1	3	9		1				3	5	4	4		9		
17-22		17	40	26		1	1/4	1		3						4					3		
17-23		3	30	8		17	1	TR	10	6						2	5	8			10		
17-24		1	46	2		19			2?.	9		TR					5	4	5		7		
17-25		18	35	14		TR	1/3	2	2	7		TR				4		13				1	← APATITE

MINERALOGY, APPROX. WT.% ☑ (or) RELATIVE ABUNDANCE ☐

SUMMARY OF X-RAY DIFFRACTION ANALYSIS

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MINERALOGY, APPROX. WT.% ☑ (or) RELATIVE ABUNDANCE ☐

17- SERIES CLAY XRD SAMPLE NO.	SMECTITE	CHLORITE & MIXED-LAYER CHL-SM UNDIFF.*	CHLORITE	MIXED-LAYER CHLORITE-SMECT.	MIXED-LAYER ILLITE-SMECTITE	ILLITE	BIOTITE	TALC	ACTINOLITE	% CHL IN M.L. CHL/SM	% IL IN M.L. IL/SM	BASAL SPACING OF A.D. SMECTITE	CH-SM ORDERED SUPERLATTICE	* MOSTLY CHLORITE BUT MAY CONTAIN SOME CHLORITE-RICH (80-90%) CHLORITE-SMECTITE
17-1	100											14.7		
17-2	100											15.0		
17-3	100											14.7		
17-4	98	2										13.8		
17-5	32	68												
17-6	23	2			75						~70	14.3		
17-7	TR	78			+22						~90			+ MAY CONTAIN SOME ILLITE OR 10Å MICA
17-8		100												
17-9	10	90										12.8	TR	
17-10	1	53			46						~90			
17-11			100											
17-12	4	96												
17-13			64	34			2	TR					TR	
17-14		100			TR		TR	TR					TR	
17-15		100						✓						
17-16	1	99						✓						
17-17		100						✓						
17-18		98		2				TR						
17-19		86		14				TR						
17-20		80		6		+14	TR	✓						
17-21		22		24		19	35	✓						
17-22		66		34									✓	
17-23		29		35		+23	13	TR					✓	+ MAY INCLUDE SOME MIXED LAYER IL-SM
17-24		11		21		19	49							
17-25		15		7		78		TR						

SUMMARY OF X-RAY DIFFRACTION ANALYSIS

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12-28-88

ROCK TYPES

17- SERIES		PPYTIC BASALT/ANDESITE	BASALT ANDESITE	DACITE, RHYODACITE	PPYTIC DACITE, RHYODACITE	MICRODIABASE	META-ANDESITE & META-BASALT	MICROGRANODIORITE	FINE-XLN HBL GRANODIORITE	BRECCIA (INTRUSION?)	MICROBRECCIA	VEIN FRAGMENTS	GOUGE, MICROBRECCIA	PPYTIC MICRO-METADIORITE	
17-1				M★				TR			m①				DACITE POST-DATES ANDESITE
17-2			MM								TR				
17-3		Ma	Ma	m							TR				
17-4		m	m	M②	M②						TR				
17-5		m	M	m	m										
17-6				MM	m					M③	M				ONE DACITE FRAG. CONTAINS GRAPHIC MICRO-GRANITE CLAST
17-7				MMa							M				
17-8		m	M	M	m			TR☒			TR				
17-9		m	Ma	M④				m⑤			M				
17-10		m	m	MM	M④			TR⑤		TR	m				
17-11		m	M	m		TR					M				TR HIGH-T GREASE
17-12		M	M	TR	TR						TR				OPHITIC CPXN IN ANDESITE
17-13				M②	m②	M					m				OPHITIC CPXN IN ANDESITE
17-14		m	M	m	m	m					M				
17-15		m	M	m		m					M				
17-16			M	m?		m		TR			M				
17-17		MM	m	TR							m				
17-18		m	‡M			m					M	m?			
17-19			TR	MM②		TR					m				GRANOPHYRE
17-20			MMa								TR				
17-21			TR?				MM				TR				TR. QTZ-BTE. HORNFELS; TR. GRAPHIC GRANITE
17-22			TR				TR		MM		TR				
17-23							M								M - METADIABASE
17-24													M		M - METADIORITE
17-25									M						WITH BIOTITE

★ PERLITIC, SOME W/ PINPOINT DEVITRIFICATION

ⓐ AMYGDALOIDAL

① ALSO POSSIBLY AMYGDULE FRAGMENTS

② PATCHY GRANOPHYRIC DEVITRIFICATION

③ COULD BE IN PART HYDROTHERMAL

☒ COULD BE GRANOPHYRIC PORTION OF DACITE

④, ⑤ COULD BE JUST DIFFERENT PARTS OF SAME ROCK

‡ POSSIBLY VERY FINE CRYSTALLINE MICRODIORITE

/ LOCALLY DEVELOPED GRANOBLASTIC REXLZN

VEINLETS & VEINLET FRAGS.

17-SERIES SAMPLE NO:	QUARTZ	CALCITE	PY - QTZ	EP ± Q, KF, CHL	SERICITE	CHL ± QTZ	WAIR ± EP, QTZ, KF, CHL	ANALCIME	SMECTITE	HEMATITE	PREHNITE ± Q, EP, KF, CHL	KF ± QTZ	ACTINOLITE ± BTZ, KF, EP		
17-1				✓				✓SM	✓						HEM ± GOE
17-2									✓	✓					
17-3		✓?							✓	✓					
17-4	✓		✓												Q - CALCITE Q - LEUCOXENE
17-5	✓	✓	✓												Q - LEUCOXENE
17-6	✓✓														QUARTZ
17-7	✓	✓		✓	✓	✓	✓								WAI - EP - CAL - CHL QTZ - KF - WAI - AB
17-8	✓	✓		✓		✓	✓								WAI - EP - CHL SIDERITE?
17-9	✓			✓		✓					✓	✓			QTZ - EP - ANH - PREHNITE
17-10	✓			✓			✓				✓		✓TR		
17-11				✓		✓	✓								Q - LEUCOXENE
17-12	✓			✓		✓					✓				EP - ANHYDRITE
17-13	✓			✓											Q - HEMATITE
17-14	✓			✓	✓?										ANHYDRITE
17-15	✓			✓		✓						✓	✓		LEUCOXENE
17-16	✓			✓		✓									
17-17	✓			✓		✓						✓			
17-18	✓			✓								✓	✓		
17-19	✓			✓								✓			
17-20	✓			✓		✓						✓	✓✓		QTZ - ACT - BTE PHENGITE?
17-21	✓											✓	✓✓		KF - QTZ BTE - QTZ
17-22				✓											
17-23	✓	✓		✓									✓		CLINOPYROXENE BTE ± QTZ
17-24															
17-25															