MINERALOGY OF THE COALINGA ASBESTOS DEPOSIT

by

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I N T R O D U C T I O N

Even the most casual visitor has little difficulty in realizing why the New Idria serpentinite body remained unrecognized for over one hundred years as one of the world's largest deposits of short-fiber asbestos. Despite its enormous size, and its high-grade nature - over 50% recoverable fiber is present in most of the deposit - the physical appearance of this body is totally unlike that of almost any other known asbestos deposit in the world. Whereas most asbestos deposits contain chrysotile in the form of cross-fiber veinlets within a massive serpentinite host-rock, such veins are essentially absent from the New Idria body. Here, the great bulk of the ore consists of soft, powdery, pellet-like agglomerates of matted, friable chrysotile, surrounding fragments and blocks of serpentinite rock. It is this highly sheared and pulverized nature which has led to the recent exploitation of

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this unusual asbestos ore, and touched off a minor "asbestos boom" in the area. By late 1959, the town of Coalinga had become the center for asbestos exploration activities, and the asbestos occurrences of the New Idria serpentinite became known as the Coalinga asbestos deposits. During this period, several large mining companies were attracted to the area and were successful in acquiring the mining rights to several hundred claims covering the entire southeastern third of this body. (See also, Munro and Reim, 1962; Merritt, 1962, Rice, 1963)

Subsequent laboratory studies by several of these companies showed that the Coalinga ore contained between 50 and 75% chrysotile, in contrast with Canadian-type ores which contain only about 5-10% usable asbestos. The Coalinga ore was comparable with Grade-7 Canadian fiber, and thus, appeared potentially useful in such products as wallboard, asbestos cement, shingles and floor tile. At the present time, three major companies are conducting mining and milling operations on this ore, including Union Carbide Corporation, Atlas Corporation, and Coalinga Asbestos Company, a joint venture between Johns-Manville Corporation and Kern County Land Company. The latter two process the ore at their mine sites by standard dry-lifting techniques, while Union Carbide hauls the ore sixty miles to King City, California, for wet processing. In addition to the conventional uses for asbestos mentioned above, the wet processed products have proved applicable to an entirely new

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spectrum of uses in the paper and plastics industries, in water purification, and in several other specialized businesses.

A mineralogical study of the Coalinga asbestos ore was begun with three main objectives: (a) the determination of the physical and chemical properties of the bulk ore and of the constituent minerals, (b) a knowledge of the distribution of minerals within the deposit itself as well as throughout the surrounding serpentinite body, and (c) the distribution of both asbestos minerals and gangue minerals during the refining and milling operations. Many of these objectives have been accomplished, and at the present time, the general mineralogy of the Coalinga asbestos ore is well known.

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E X P E R I M E N T A L

SAMPLE COLLECTION AND PREPARATION

During this investigation, more than 500 individual samples were examined from all parts of the ore body as well as from the surrounding serpentinite massif. Hand specimens of both the high grade ore and of the serpentinite gangue material associated with it were also collected by the authors during the summers of 1962 and 1963. Numerous parts of the surface weathering zone were also sampled extensively, as were many of the residual serpentinite knobs and outcrops scattered throughout the deposit. Material was also collected from both the mine sites and the stockpiles of most of the companies engaged in mining the Coalinga ore. An integral part of this program has been the study of interval samples from over 150 rotary drill holes, located in a systematic manner across Union Carbide's property. A total of more than 2,100 individual samples of this type were collected and examined in the field by Messrs. W. T. Cohan and M. Genes. A large sample representing half of the material recovered from the drill hole was collected for each ten-foot interval of the hole and split immediately to about 25 pounds. With alternate grinding, screening, and splitting, the sample was reduced in size to about five pounds of -10 mesh material.

The preparation of samples of serpentinite rich in chrysotile asbestos posed a number of problems, since it was extremely difficult (in many cases, impossible) to prepare powders by ordin-

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ary grinding techniques. It was often necessary to reduce the particle size of samples to about -10 mesh by dry grinding in a Waring Blendor. Further comminution was accomplished by grinding in a Pitchford Selective Particle Size grinder, although samples pulverized to -325 and -400 mesh became highly contaminated from the tungsten carbide mill and balls. In many cases, mineralogical examinations were made directly on pressed filter cakes prepared by mixing the sample with water for several minutes in a Waring Blendor and filtering immediately.

For many analyses, it was necessary to prepare highly purified samples of chrysotile from the ore, essentially free of gangue minerals. This was accomplished by dispersing the sample in an aqueous solution of aluminum acetate, followed by a decantation of the dispersable fiber from the coarser grained magnetite and serpentine. This technique represents a modification of procedures reported in U. S. Patent No. 2,661,287. (Barbaras, 1953) In this manner, nearly pure chrysotile can be separated from the rock fragments. The dispersed fraction is decanted from the sink fraction, flocculated with sodium carbonate and filtered. By means of different settling times, or different centrifugation conditions, various degrees of separations can be accomplished by this technique.

APPARATUS

All X-ray diffraction studies were made with a Norelco High Angle Diffractometer or a 114.6-mm diameter powder camera,

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using Ni-filtered CuKα radiation. Powdered samples were either slurried on a glass slide or packed into stainless steel holders and X-rayed from 60° to 2°2θ at a scanning rate of 2° per minute. One-inch circles cut from dried filter cakes were examined directly by pasting the discs to glass sample holders. Samples prepared thusly were found to be highly prone to orientation, and consequently, the basal spacings of the serpentine were emphasized in the X-ray pattern. Orientation effects were somewhat reduced by spinning the sample in the X-ray beam by means of a rotating specimen holder, and also by using packed holders of -450 mesh material.

Infrared absorption analyses were made with a Perkin-Elmer Model 221, double-beam, infrared spectrophotometer with rock salt optics. The KBr pellet technique was used in which the sample concentration was held constant at 0.25 weight percent. Petrographic analyses were made using standard, research model, Leitz polarizing microscopes. A Powertron 300-watt Ultrasonic Cleaner was used frequently in this study to disaggregate specimens and to assist in the dispersion of particular serpentine samples.

Extensive electron microscopic investigations were made by Mr. W. Roettgers using a Siemens Research Model electron microscope. Both water suspension and pre-shadowed carbon-replica techniques were employed in the preparation steps. Electron diffraction studies were also made of selected samples using the selected-area-diffraction technique.

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Differential thermal-analysis patterns of numerous samples were obtained using a calcined kaolin as a reference material, and were electronically recorded on a X-Y recorder as a function of emf. The temperature was controlled by means of a saturated core, reactor-type controller, which operated a cam adjustment to raise the temperature at a constant rate of 10°/minute. The temperature was measured by a Pt-Pt13Rh thermocouple. Although no rigorous attempt was made to define the temperature exactly, quartz run in the same apparatus under identical conditions exhibited the alpha-beta transition endotherm at 571°C. Thus, the measured temperatures are probably accurate to within ±5°C. In reporting the temperature of reactions, the intersecting tangents method was used, as illustrated in Figure 32.

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CHARACTERIZATION OF SERPENTINE MINERALS

The unequivocal identification of the several members of the serpentine group is a difficult (and at times, a near-impossible) task, which is made even more complex by the presence of two or more serpentine polymorphs in the same specimen. The occurrence of several different serpentine minerals in most specimens from the Coalinga asbestos deposit has necessitated the development of a reliable identification scheme, based upon a combination of precise X-ray-diffraction, electron-microscopic and electron-diffraction techniques. It could not have been developed without a great deal of fundamental work on standard samples of serpentine minerals obtained from many workers, both in this country and abroad. Its complexity, and the time involved for each sample, have precluded routine use, and only a relatively small number of selected specimens from the deposit have been completely characterized in this manner.

NOMENCLATURE

The word "asbestos" is a commercial term for a group of fibrous silicate minerals that are both fire-proof and capable of being processed into flexible fibers. Although six different minerals are currently mined as "asbestos", the mineral chrysotile accounts for more than 95% of the world's production. Most commercial deposits of chrysotile asbestos are found as cross-fiber or slip-fiber veins within large bodies of serpentinite rock. The

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veins vary in size from fractions of a millimeter to several inches; their quantity and size determine the economic potential of the ore body.

Chrysotile asbestos is the fibrous member of the serpentine group of minerals, which also includes the platy minerals, lizardite and antigorite. All members of this group have the same general formula, $Mg_3Si_2O_5(OH)_4$, with small amounts of nickel and iron substituting for magnesium. The serpentine structure, shown in Figure 1, consists of a unit magnesium hydroxide layer (brucite layer) connected to a unit silicon-oxygen layer (silicate layer) to form an infinite two-dimensional sheet. In the case of chrysotile, small differences in the unit dimensions of the two layers result in a curvature of the sheet with the brucite layer on the outside. Therefore, chrysotile occurs as tubular fibers of various lengths. The average fibril has an inner diameter of 110 Å and an outer diameter of 260 Å, or a wall thickness of about ten layers of the basic 1:1 serpentine sheet. Whittaker and Zussman (1956) have subdivided chrysotile into three forms: clinochrysotile, orthochrysotile, and parachrysotile, which differ primarily in the mode of stacking of the unit layers. The differentiation among the forms is not always possible from X-ray data and has not been attempted in this investigation.

A second polymorph of serpentine, lizardite, occurs as fine-grained plates and laths and is characterized by a one-layer

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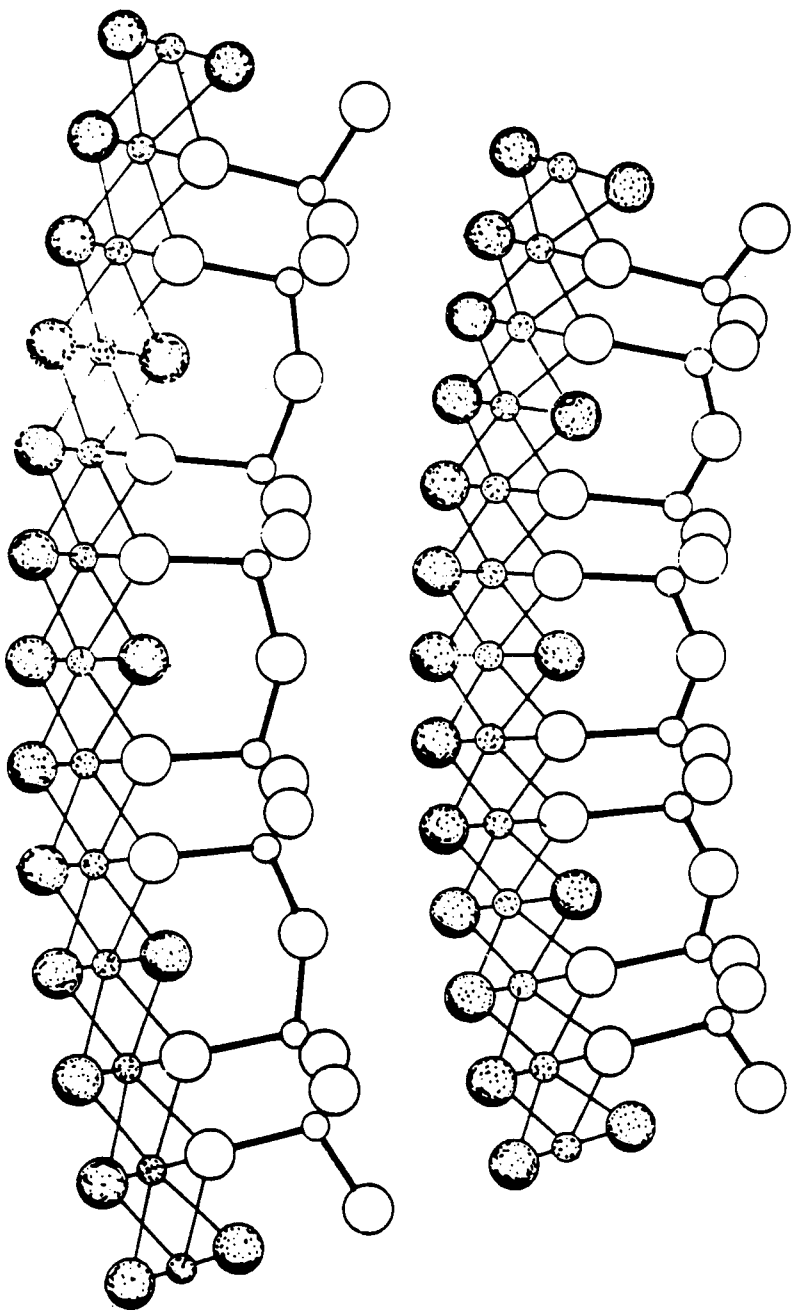


FIGURE 1. Crystal structure of chrysotile asbestos

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unit cell with orthohexagonal symmetry, where beta = 90°00'. Presumably, the mismatch of the unit layers is alleviated by the presence of nominal amounts of larger ions in the silicate layer (i.e., Al^{+3}) and/or smaller ions in the brucite layer (i.e., Fe^{+2}, Fe^{+3}, Al^{+3}). The details of the crystal structure and the stacking arrangements of lizardite are not well known, and several sub-varieties are thought to exist. Among these is the six-layer orthochrysotile described by Brindley and von Knorring (1954). Although it is easily confused with antigorite or massive chrysotile in hand specimen, lizardite can be distinguished from both chrysotile and antigorite by film X-ray diffraction or electron diffraction. Lizardite is the major constituent of many serpentinites and comprises a large proportion of the massive, green serpentine associated with cross-fiber chrysotile veins.

Antigorite is structurally distinct from either chrysotile or lizardite in that the "a" dimension of its unit cell is quite large, about 40 Å. Chemically, it also differs slightly from the ideal serpentine composition, containing significantly more hydroxyl than chrysotile (Bates, 1959); and, therefore, it may not be a true polymorph of serpentine at all. Its similarity to serpentine can be demonstrated, however, by deriving a pseudo unit cell wherein the "a" dimension is about 5.31 Å, suggesting that antigorite is merely a distorted form of the basic serpentine lattice. Although antigorite usually occurs as laths or plates,

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fibrous varieties (picrolite) have been described. The multiplicity of reflections of the antigorite super-lattice makes its distinction from chrysotile or lizardite possible, by X-ray diffraction or electron diffraction, although mixtures of two or more serpentine polymorphs can present great difficulties.

Much of the foregoing discussion has been taken from Deer, Howie and Zussman (1962, Vol. II) to which the reader is referred for further details.

Although chrysotile is readily distinguished from other serpentine minerals by its tubular-fibrous habit (by electron microscopy), the similar morphologies of lizardite and antigorite preclude their differentiation by this technique alone. It is necessary to employ a combination of techniques, including film X-ray diffraction, electron diffraction, and electron microscopy, to make an unequivocal identification. No one technique is by itself completely satisfactory, especially where mixtures of two or more of the members are involved. In this respect, the present studies have shown that mixtures are the rule rather than the exception; all combinations of serpentine minerals have been encountered in even the most highly purified samples and in the type specimens from around the world.

X-RAY DIFFRACTION IDENTIFICATION

In Table I, the X-ray diffraction patterns of several standard chrysotile samples are compared with the data listed by

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TABLE I. X-RAY DIFFRACTION DATA FOR STANDARD CHRYSOTILE

	CHRYSOTILE ZERMALL, SWITZERLAND[1] Cross-fiber ASTM 10-381		CHRYSOTILE THETFORD QUEBEC[2] Platy 367-2-1		CHRYSOTILE THETFORD QUEBEC Cross-fiber 568-30-1-1		CHRYSOTILE CASSIAR BRIT. COL.[3] Cross-fiber 367-92-1-5		CHRYSOTILE COALINGA CALIFORNIA[3] Cross-fiber 487-52-18-1		CHRYSOTILE COALINGA CALIFORNIA Green-bladed 487-34-3		CHRYSOTILE COALINGA CALIFORNIA[3] Fiber 367-49-1-1		CHRYSOTILE STRAGARI YUGOSLAVIA[3] Fiber 487-66-1	
(hkl)	"d"	I/I_o	"d"	I/I_o	"d"	I/I_o	"d"	I/I_o	"d"	I/I_o	"d"	I/I_o	"d"	I/I_o	"d"	I/I_o
002	7.36	10	7.28	10	7.31	10+	7.25	10+	7.31	10	7.31	10	7.28	10+	7.34	10+
020	4.58	5	4.56	4	4.55	4	4.54	4	4.56	3	4.59	4	4.56	4	4.53	4
004	3.66	10	3.65	6	3.65	6	3.65	6	3.65	7	3.66	6	3.65	8	3.65	8
	-	-	3.40	1	3.40	<1	-	-	-	-	-	-	-	-	-	-
Talc	-	-	3.13	<1	-	-	-	-	-	-	-	-	-	-	-	-
130	2.66	4	2.64	<1	-	-	-	-	-	-	-	-	2.65	<1	-	-
201	2.594	4	-	-	2.60	3	2.60	2	2.60	2	2.61	<1	2.60	2	2.59	3
202	2.549	5	2.54	<1	2.54	2	-	-	2.50	1	2.55	<1	2.53	2	-	-
202	2.456	8	2.445	4	2.45	4	2.45	4	2.45	2	2.46	5	2.45	4	2.45	4
203	2.282	3	2.28	<1	-	-	-	-	-	-	2.28	<1	2.27	<1	-	-
204	2.215	3	2.21	1	2.21	<1	2.21	<1	-	-	2.22	<1	2.21	1	2.21	<1
204	2.096	5	2.09	2	2.09	1	2.09	1	2.09	1	2.10	2	2.09	3	2.09	1
008	1.829	3	1.819	<1	-	-	-	-	1.826	1	1.829	<1	1.823	1	1.828	<1
206	1.748	5	1.740	2	1.743	<1	1.738	1	1.743	<1	1.749	2	1.742	3	1.731	1B
	-	-	-	-	1.614	<1	-	-	-	-	-	-	-	-	-	-
060	1.536	8	1.534	5	1.535	6	1.534	6	1.536	6	1.540	5	1.533	6	1.535	6
208	-	-	1.508	<1	-	-	-	-	-	-	1.509	<1	-	-	-	-
00.10	1.465	3	1.460	<1	-	-	-	-	-	-	1.467	1	1.463	1	-	-
402	1.317	4	1.316	3B	1.316	1	1.316	2	1.315	2B	1.320	2B	1.315	3B	1.320	2B
	-	-	-	-	-	-	-	-	-	-	-	-	1.274	<1	-	-
	-	-	-	-	1.043	1B	-	-	-	-	1.047	<1B	1.196	<1	0.997	<1
531	-	-	0.995	<1	1.000	1B	0.992	<1B	0.995	<1	0.995	<1B	1.006	1B	0.997	<1
	-	-	0.889	<1	0.886	1B	-	-	0.886	1	0.888	1B	0.885	1B	0.887	1

(1) Data listed in Whittaker and Zussman (1956) and represent a composite of two chrysotiles: one from Zermall, Switzerland, and one from Reichenstein, Silesia.

(2) Sample supplied by G. Faust, similar to the Coalinga green-bladed material.

(3) Samples purified by dispersion techniques.

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Whittaker and Zussman (1956). The patterns, obtained by film techniques, are almost identical; most of the minor differences are attributable to the inability to measure certain faint lines from the films. It is also significant that no differences between the cross-fiber and powdery chrysotiles were noted. A striking characteristic of almost every chrysotile sample is the diffuse nature of the film patterns. The X-ray diffraction patterns of chrysotile and lizardite are very similar, but small differences do exist and can be used to distinguish the two polymorphs. With reference to Tables I and IV, the positions of the (202) and (204) reflections are critical, chrysotile having lines at 2.45 Å and 2.09 Å, respectively, while the corresponding lizardite lines lie at 2.50 Å and 2.15 Å. The lizardite pattern is also characterized by a strong doublet at 1.531 Å and 1.500 Å, corresponding to the (060) and (208) reflections, while chrysotile has only a strong (060) reflection at 1.535 Å.

X-ray diffraction data for several lizardite specimens, including two received from J. Zussman, are listed in Table II and compared with the data reported by Whittaker and Zussman (1956). From these data, it appears that the Kenneck Cove, Cornwall sample is essentially pure lizardite contaminated only with a small amount of talc. The Snarum material, however, appears to be a mixture of lizardite and chrysotile, exactly as is the specimen described by the above authors (sample 15, page 117). The small amount of chrysotile in the Snarum material is indicated by the presence of

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TABLE II. X-RAY DIFFRACTION DATA FOR STANDARD LIZARDITES

LIZARDITE CORNWALL 568-22-2 Received from J. Zussman, 7/64		LIZARDITE CORNWALL (14) (Whittaker and Zussman, 1956)		LIZARDITE SNARUM 568-22-1 Received from J. Zussman, 7/64		LIZARDITE SNARUM (15) (Whittaker and Zussman, 1956)		LIZARDITE NEW ZEALAND 79-NZ-62-2 Received from R. G. Coleman		
"d"	I/I_o	"d"	I/I_o	"d"	I/I_o	"d"	I/I_o	"d"	I/I_o	(hkl)
9.36	3	-	-	-	-	-	-	-	-	Talc
7.34	10	7.36	vs	7.28	10+	7.35	vs	7.28	10	002
4.59	5	4.62	ms	4.59	5	4.61	m	4.58	4	020
3.88	3	3.89	w	3.90	2	3.90	mw	3.88	1	022
3.63	6	3.64	vs	3.64	10	3.66	vs	3.65	8	004
3.11	2	-	-	3.16	<1	-	-	-	-	Talc
-	-	-	-	-	-	-	-	3.01	2	-
2.86	<1B	-	-	2.85	<1	2.85	w	-	-	024
2.64	1	2.65	mw	2.65	1	2.66	mw	2.70	2	130
2.59	<1	-	-	-	-	-	-	2.59	1	-
2.49	10	2.495	s	2.50	9	2.499	s	2.50	5	202
-	-	-	-	2.44	3	2.446	m	2.45	5	202*
-	-	-	-	-	-	-	-	2.35	<1B	203
-	-	2.299	w	-	-	-	-	-	-	040
-	-	-	-	-	-	-	-	2.20	1	204
2.15	6	2.148	m	2.15	4	2.150	ms	2.15	2	204
-	-	-	-	2.09	1	2.092	w	2.09	1	204*
-	-	-	-	-	-	-	-	1.957	1	205
-	-	-	-	-	-	-	-	1.907	<1	-
1.830	<1	1.830	w	-	-	1.826	w	1.824	<1	008
1.792	2	1.794	mw	1.796	2	1.795	m	1.795	1	206
1.735	1	1.737	mw	1.740	1	1.740	w	1.743	1	310
1.691	1B	1.695	vw	1.694	<1	1.699	w	1.674	<1	028
-	-	-	-	-	-	-	-	1.610	2	-
1.531	7	1.534	ms	1.535	7	1.535	s	1.536	5	060
1.500	6	1.503	m	1.503	5	1.503	ms	1.507	2	208
1.461	<1	1.460	vw	1.462	<1	1.462	w	1.463	<1	00.10
1.414	1	1.415	w	1.414	1	1.415	w	1.420	<1	064
1.326	<1	1.328	w	-	-	1.328	w	1.348	<1	400
1.306	3	1.307	m	1.309	3	1.308	m	1.313	2B	402
1.278	1	1.279	w	1.280	1	1.282	mw	1.283	<1	20.10
1.248	<1B	1.252	vw	1.249	<1	1.250	vw	-	-	404
-	-	1.218	vw	1.218	<1	1.217	vvw	1.220	<1	00.12
1.165	1	1.167	vw	1.165	1	1.168	vw	1.167	<1	406
-	-	-	-	-	-	-	-	1.119	<1	-
-	-	-	-	-	-	-	-	1.103	<1	-
1.073	1	1.073	vvw	1.073	<1	1.074	vvw	-	-	408
1.057	<1	1.056	vvw	1.059	<1	1.058	vvw	-	-	510
0.994	2	0.994	w	0.995	2	0.995	w	0.997	<1	531
0.968	1	-	-	0.970	<1	-	-	0.970	<1	
0.954	1	-	-	0.954	<1	-	-	-	-	

* Chrysotile

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two additional lines in the film pattern at 2.44 Å and 2.09 Å, corresponding to the (202) and (204) reflections of the chrysotile lattice, where beta = 93°16'. The analogous lines of lizardite occur at 2.50 Å and 2.15 Å. Both sets of lines are clearly visible in the pattern of the Snarum material, while only the lizardite lines are present in the pattern of the Cornwall sample. Lizardite also differs from chrysotile by having a weak reflection at 3.88 Å, and a strong pair of lines at 1.531 and 1.500 Å. Other minor differences in line position and/or intensity are also present and can be observed by a direct comparison of lm patterns, but none are so distinctive as those mentioned above.

The sample of New Zealand lizardite listed in Table II, received from R. G. Coleman of the U. S. Geology Survey, can also be seen to be a mixture of chrysotile and lizardite, similar to the material from Snarum, Norway. Electron micrographs show an abundance of chrysotile fibers in this particular sample, along with a smaller amount of platy serpentine. During this study, a hand-picked sample of cross-fiber chrysotile from the Globe, Arizona, district was purified by chemical dispersion techniques and separated into float and sink fractions. From the X-ray diffraction data listed in Table V, it can be seen that the float fraction consists of pure chrysotile, while the sink portion contains both chrysotile and lizardite, indicated by the strong lizardite lines at 3.85, 2.50, 2.14, and 1.503 Å. These results point out the intimate

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mixtures of serpentine polymorphs that can occur, and that could be completely overlooked without a critical examination of the specimens.

Four standard antigorite samples have been used in this study, including two from New Zealand provided by R. G. Coleman, one from the type locality, Val Antigorio, Italy supplied by G. T. Faust of the U. S. Geological Survey, and a purified sample from Santa Rita Peak, within the Coalinga asbestos deposit itself. The X-ray diffraction data for these specimens are listed in Table III and compared with literature values for antigorite reported by Zussman (1954) and Whittaker and Zussman (1956). From film X-ray-diffraction patterns, antigorite is easily distinguished from chrysotile and lizardite, although mixtures of antigorite with other serpentines usually offer more difficulties. The position and intensities of several major reflections, as well as an abundance of minor reflections, allow the distinction to be made if film patterns are used. The presence of a strong doublet at 1.562 and 1.536 Å, corresponding to the (24·3·0) and (060) reflections of the large monoclinic unit cell of antigorite, is characteristic. As seen in Table IV, lizardite has a strong doublet at 1.531 and 1.500 Å, while chrysotile has only a single strong line at 1.535 Å. The exact position of the strong reflection at about 2.5 Å is also indicative of the type of serpentine present; antigorite has a line at 2.52 Å, lizardite a line at 2.49 Å, and chrysotile a line at 2.45 Å - small

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TABLE III. X-RAY DIFFRACTION DATA FOR STANDARD ANTIGORITES

ANTIGORITE Cross River New Zealand ASTM 10-402 Zussman (1954)		ANTIGORITE Taberg, Sweden (29) Whittaker and Zussman (1956)		ANTIGORITE Mikonui New Zealand (30)		ANTIGORITE Val Antigorio Italy 367-2-2		ANTIGORITE Griffin Rng. New Zealand 487-39-5 (94-NZ-62)		ANTIGORITE Milford Snd. New Zealand 487-39-6 (38-NZ-62-5)		ANTIGORITE Santa Rita Peak Coalinga, Calif. 487-52-8	
"d"	I/I_o	"d"	I/I_o	"d"	I/I_o	"d"	I/I_o	"d"	I/I_o	"d"	I/I_o	"d"	I/I_o
7.28	9	7.28	vs	7.30	vs	7.23	10	7.25	10	7.23	10	7.28	10
6.46	<1	6.40	w	-	-	-	-	-	-	6.73	<1	-	-
-	-	-	-	-	-	-	-	-	-	6.13	1	-	-
5.82	1	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	5.19	<1	5.26	1	-	-
4.64	3	4.64	mw	4.66	m	4.62	2	4.59	3	4.61	5	4.61	3
4.26	2	4.24	w	4.25	w	4.23	2	4.24	3	4.18	4	4.27	2
3.91	1	-	-	-	-	-	-	-	-	-	-	-	-
3.60	8	3.61	vs	-	-	3.60	9	3.62	6	3.62	10	3.62	8
-	-	-	-	-	-	3.13	<1 Talc	-	-	3.47	1	-	-
-	-	-	-	-	-	2.89	<1	-	-	2.87	<1	-	-
2.60	2	2.60	w	2.67	vvw	-	-	-	-	-	-	-	-
2.51	10	2.53	vs	2.53	ms	2.52	10	2.52	9	2.53	10	2.52	10
2.45	3	2.45	w	-	-	2.45	1	2.44	1	2.43	2	2.46	1B
-	-	2.42	2	2.42	w	-	-	-	-	-	-	-	-
2.39	2	2.38	vw	-	-	2.39	1	2.38	<1	2.37	1	-	-
2.31	<1	-	-	-	-	-	-	-	-	-	-	-	-
2.24	<1	2.25	vw	-	-	2.23	<1	-	-	-	-	-	-
2.21	1	2.21	w	-	-	2.20	<1	-	-	-	-	2.21	<1
2.17	5	2.163	m	-	-	2.16	4	2.16	4	2.16	5	2.16	2
2.15	3	-	-	-	-	-	-	-	-	-	-	-	-
2.12	<1	-	-	-	-	-	-	-	-	-	-	2.10	1
-	-	-	-	2.03	mw	-	-	-	-	-	-	-	-
1.831	2	1.835	w	-	-	1.829	1B	1.829	1	1.843	1	1.824	1
1.811	1	1.813	w	1.819	mw	-	-	-	-	1.812	1	-	-
1.780	3	1.779	m	-	-	1.778	1	1.776	1	1.779	1	1.782	1
1.740	1	1.732	mw	-	-	1.738	1	1.740	1	1.719	1B	1.745	1
-	-	1.566	ms	1.561	m	1.564	2	1.562	4	1.566	5	1.560	4
1.554	5	-	-	-	-	-	-	-	-	-	-	-	-
1.533	4	-	-	-	-	1.543	1	1.536	4	1.541	5	1.540	4
1.517	2	1.525	w	1.528	w	1.523	<1	1.522	<1	1.526	<1	1.521	<1
1.500	2	1.509	w	1.508	mw	1.508	1	1.506	<1	1.508	1	1.507	1
1.492	1	1.494	w	-	-	1.491	<1	-	-	-	-	-	-
1.477	1	1.477	vw	-	-	1.473	<1	-	-	-	-	-	-
1.461	1	-	-	-	-	-	-	1.463	<1B	-	-	-	-
1.447	1	1.449	vw	1.453	w	1.443	<1	-	-	1.451	1	1.455	<1
1.415	<1	-	-	-	-	1.419	<1	1.414	<1	1.417	1	1.414	1
-	-	-	-	-	-	1.389	<1	1.384	<1	1.383	<1	-	-
1.339	<1	-	-	-	-	1.343	<1	1.342	<1	1.348	1	-	-
1.315	4	-	-	-	-	1.320	2	1.315	3	1.315	3	1.316	2
1.300	1	-	-	-	-	1.303	1	1.298	<1	1.300	1	1.301	<1

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TABLE IV. STANDARD X-RAY DIFFRACTION DATA FOR SERPENTINE MINERALS

ANTIGORITE NEW ZEALAND 487-39-5 "d"	I/I_o	LIZARDITE CORNWALL 568-22-2 "d"	I/I_o	CHRYSOTILE THETFORD 568-30-1-1 "d"	I/I_o	LIZARDITE/ CHRYSOTILE INDICES (hkl)
7.25	10	7.34	10	7.31	10+	002
5.19	<1	-	-	-	-	
4.59	3	4.59	5	4.55	4	020
4.24	3	-	-	-	-	
-	-	3.88	3	-	-	022
3.62	6	3.63	6	3.65	6	004
-	-	-	-	3.40	<1	
-	-	2.86	<1B	-	-	024
-	-	2.64	1	-	-	130
-	-	2.59	<1	2.60	3	201
2.52	9	-	-	2.54	2	202
-	-	2.49	10	-	-	202
2.44	1	-	-	2.45	4	
2.38	<1	-	-	-	-	
-	-	-	-	2.21	<1	$20\bar{4}$
2.16	4	2.15	6	-	-	
-	-	-	-	2.09	1	204
1.829	1	1.830	<1	-	-	008
-	-	1.792	2	-	-	
1.776	1	-	-	-	-	206
1.740	1	-	-	1.743	<1	
-	-	1.735	1	-	-	
-	-	1.691	1B	-	-	028
-	-	-	-	1.614	<1	
1.562	4	-	-	-	-	
1.536	4	1.531	7	1.535	6	060
1.522	<1	-	-	-	-	
1.506	<1	1.500	6	-	-	208
1.463	<1B	1.461	<1	-	-	00.10
1.414	<1	1.414	1	-	-	064
1.384	<1	-	-	-		
1.342	<1	1.326	<1	-	-	400
1.315	3	1.306	3	1.316	1	$40\bar{2}$
1.298	<1	1.278	1	-	-	20.10
1.263	1	1.248	<1B	-	-	404
1.207	1	1.165	1	-	-	
1.152	<1	1.073	1	-	-	
1.071	<1	1.057	<1	1.043	1B	
1.055	1	0.994	2	1.000	1B	
1.001	1	0.968	1	-	-	
0.972	<1	0.954	1	-	-	
0.951	<1	-	-	-	-	
0.906	<1	-	-	-	-	
0.895	<1	-	-	0.886	1B	
0.887	<1					

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but observable differences. The presence of magnetite in a sample, however, may cause difficulties, since the major reflection of magnetite occurs at 2.53 Å.

Although natural mixtures of antigorite and lizardite have only infrequently been reported, chrysotile-antigorite and chrysotile-lizardite assemblages are relatively common in nature. To determine whether or not such mixtures can be detected by X-ray diffraction techniques, a synthetic mixture of the New Zealand antigorite (487-39-6) and the Coalinga green-bladed chrysotile (487-34-3) was prepared. From the X-ray diffraction data listed in Table V, the presence of both phases can be determined. Although many of the lines overlap one another, critical reflections corresponding to both polymorphs can be detected in the film pattern.

Standard X-ray-diffraction data for the three serpentine minerals are listed in Table IV. The major lines of each phase, the presence and positions of which are critical for identification, are underlined. It should be emphasized that although reliable identifications may be made by comparing tabulated X-ray data, much more unequivocal characterizations can be made if film patterns of the unknown samples are compared directly with those of standard materials.

Throughout the previous discussion, the X-ray identifications of the serpentine minerals have been based upon the comparison of film diffraction patterns with those of standard minerals. In

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TABLE V. X-RAY DIFFRACTION DATA FOR SEVERAL SERPENTINE SAMPLES

CHRYSOTILE Purified Cross-fiber Globe, Ariz.[1] 568-28-1		CHRYSOTILE + LIZARDITE Sink Fraction Globe, Ariz.[1] 568-28-2		CHRYSOTILE + ANTIGORITE 1:1 Synthetic Mixture[2] 487-34-4	
"d"	I/I_o	"d"	I/I_o	"d"	I/I_o
7.34	10+	7.31	10	7.25	10
4.55	4	4.58	4	4.60	3
-	-	-	-	4.19	2
-	-	3.85	<1	3.87	<1
3.65	6	3.65	8	3.62	8
3.33	1	-	-[3]	-	-
-	-	3.03	2	-	-
2.65	1B	2.66	2B	2.73	1
2.58	2	-	-	-	-
-	-	2.50	5	2.53	6
2.45	4	2.45	3	2.44	4
-	-	2.28	1	2.27	2
-	-	-	-	-	-
-	-	2.14	2	2.16	1
2.09	1	2.10	1	2.09	<1
1.819	1	1.828	1	1.828	1B
-	-	1.796	2	1.781	<1
1.752	1B	1.743	1	1.743	2
-	-	-	-	1.704	1
-	-	-	-	1.566	3
1.533	8	1.535	6	1.536	4
-	-	-	-	-	-
-	-	1.503	3	1.507	1
-	-	1.463	<1	-	-
-	-	-	-	1.451	1
-	-	-	-	1.425	1
-	-	1.416	1	-	-
1.315	3B	-	-	1.315	3
-	-	1.309	2B	-	-
-	-	-	-	1.299	<1
-	-	1.217	<1	-	-
-	-	1.059	<1	-	-
0.996	1B	0.995	2	1.013	<1

1) Sample collected in NE 1/4, SW 1/4 Sect. 21, T6N, R14E, Gila Co., Arizona

2) Green-bladed chrysotile from Coalinga, Calif. (487-34-3) and New Zealand antigorite (487-39-6) used for this synthetic mixture.

3) Calcite

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general, film patterns have been found to be superior to diffractometer traces for identification, since many more reflections are visible, and a comparison of the position and intensities of many of the weaker lines can be made with greater precision. The film techniques also minimized orientation effects; thus, many non-basal reflections of the lattice can be measured. Although there are several disadvantages to the film technique, it is strongly recommended over the diffractometer-trace technique for serpentine minerals, for anything more than a cursory examination and identification.

ELECTRON MICROSCOPIC IDENTIFICATION

From electron microscopic examination, little difficulty is encountered in the identification of chrysotile, since its tubular, fibrous habit is quite distinctive. (Bates, Sand and Mink, 1950) Typical electron micrographs of various chrysotile materials are shown in Figures 2 and 3 which show a large variation in tube shape, from the long, thin tubes in the former to the short, stubby tubes in the latter. The identification of the nonfibrous varieties of serpentine, however, is not as easy by electron microscopic techniques, and often no distinction can be made between lizardite and antigorite. Electron micrographs of lizardite samples are shown in Figures 6 and 7. Hexagonal outlines are frequently characteristic of lizardite, although many particles are completely anhedral. In general, the antigorite grains, shown in Figures 4 and 5, are also completely formless, although characteristic Moiré patterns are

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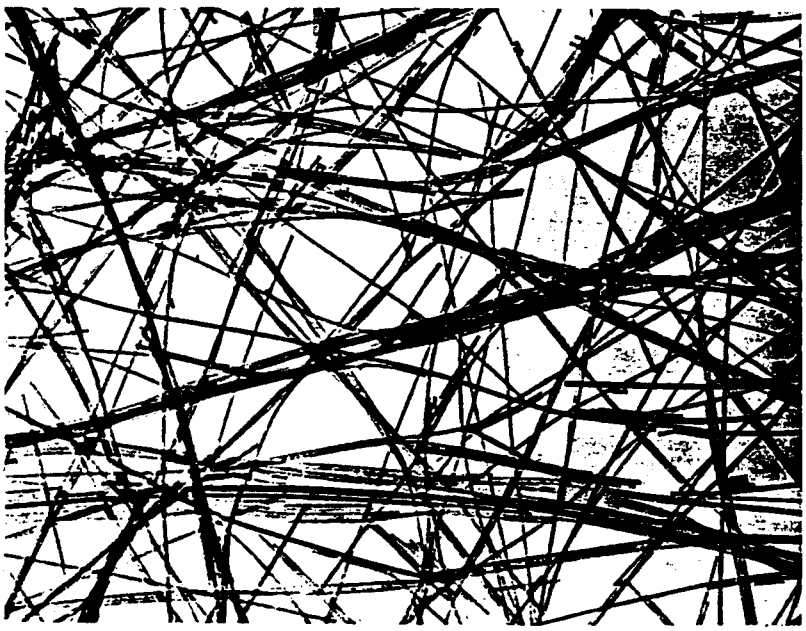


FIGURE 2. Electronmicrograph of chrysotile from the Coalinga asbestos deposit. Magnification = 15,500 X.

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FIGURE 3. Electronmicrograph of chrysotile from the serpentinite rock fragments of the Coalinga asbestos deposit. (248-43-4). Magnification = 19,500 X.



FIGURE 4. Electron micrograph of antigorite from Val Antigorio, Italy (367-2-2). Magnification = 32,000 X.

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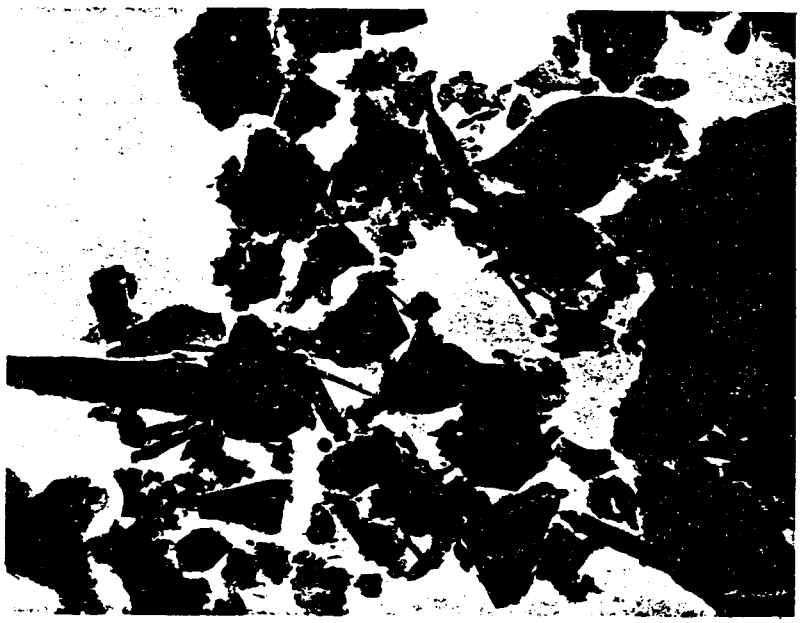


FIGURE 5. Electron micrograph of antigorite from Santa Rita Peak, Coalinga asbestos deposit. (487-52-8). Magnification = 18,000 X.

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FIGURE 6. Electron micrograph of lizardite from Cornwall, England. (568-22-2). Magnification = 32,000 X. Note the curling of the edges of the lizardite plates in this sample.

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FIGURE 7. Electron micrograph of lizardite from Snarum, Norway. (568-22-1). Magnification = 32,000 X.

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commonly observed from larger antigorite plates.

ELECTRON DIFFRACTION IDENTIFICATION

Probably the most unequivocal identification of the serpentine polymorphs has been achieved by means of selected-area electron diffraction, in which individual grains or areas within an electron microscope field are selected for diffraction, excluding the rest of the field. This technique has been used successfully by Zussman, Brindley and Comer (1957), who related the electron diffraction patterns of the serpentines to their crystal structures.

Electron micrographs, and the corresponding diffraction patterns, of typical chrysotile samples are shown in Figures 8 and 9. The above authors point out that "The diffraction patterns resemble closely those obtained by X-rays with the beam normal to a fibre bundle. Reflections are distributed along 'layer-lines', the spacing of which corresponds to the repeat distance a = 5.32 Å along the fibre axis." The oriented layer lines of the chrysotile pattern are quite distinctive and are strongly characteristic of this polymorph. Diffraction patterns resulting from two or more chrysotile particles may show the effect of the different orientations of the individual fibers. Although a close examination of electron diffraction patterns can also yield information as to the exact chrysotile polytype (ortho, clino or para), no such attempt has been made in this study.

The electron diffraction patterns of lizardite specimens,

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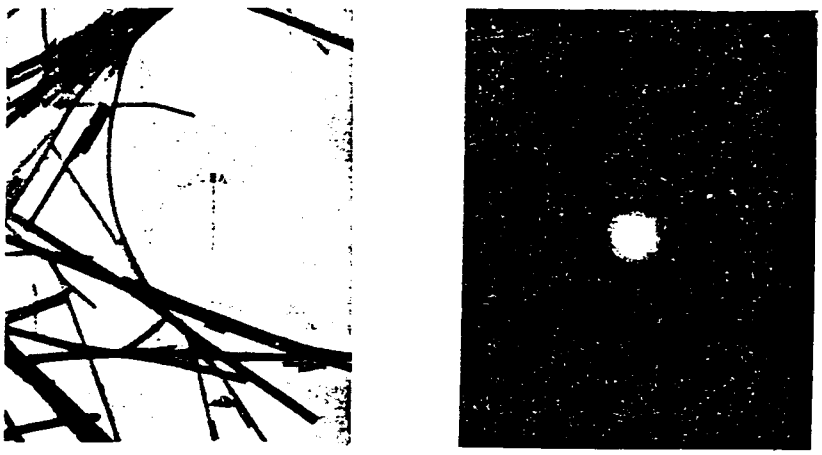


FIGURE 8. Electron micrograph and diffraction pattern of chrysotile from Thetford, Quebec. (568-30-1-1) Magnification = 21,000 X.

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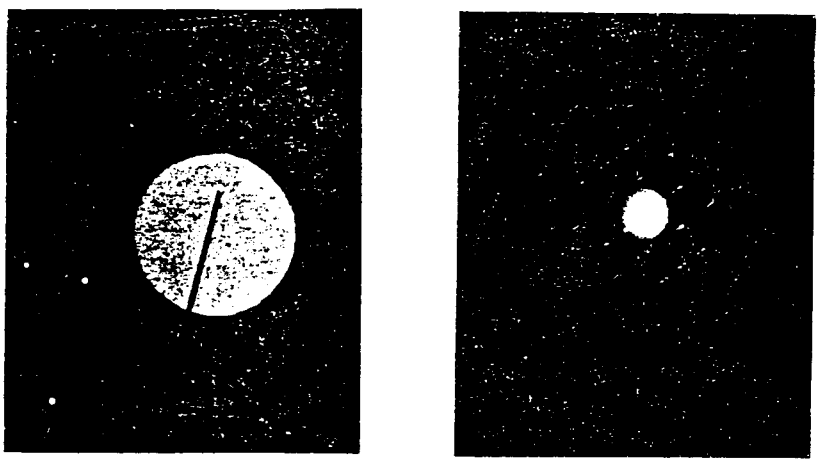


FIGURE 9. Electron micrograph and diffraction pattern of chrysotile from the Coalinga asbestos deposit. (Green-bladed material). Magnification = 21,000 X.

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shown in Figures 10 to 13, are relatively simple and show a hexagonal array of spots corresponding to a net having the unit-cell dimensions listed by Deer, Howie and Zussman (1962). In many cases, several overlapping particles of lizardite give rise to distinct sets of spots, slightly rotated from one another, but the characteristic hexagonal network is plainly visible (Figure 11). Although many particles of lizardite occur as formless thin plates wherever well-formed hexagonal platelets have been observed, the material invariably turns out to be lizardite. This habit appears to be characteristic of this polymorph. It is interesting that well-formed lizardite has been observed as an impurity in the Thetford chrysotile, the antigorite from Santa Rita Peak (Figure 12), the green-bladed chrysotile from the Coalinga deposit, and in the type antigorite material from Val Antigorio (Figure 13).

Antigorite diffraction patterns (Figures 14-16) are unique in that clusters of closely spaced spots occur along layer lines at regular intervals corresponding to the superlattice periodicity of the enlarged antigorite unit cell. Zussman, Brindley and Comer (1957) measured numerous values for the a_o dimension of antigorite samples and found that, although preferred values lay between 33 and 45 Å, many values ranged as high as 100 Å. Overlapping plates of antigorite also result in multiple diffraction patterns; however, the multiplicity of spots in a hexagonal arrangement is quite characteristic.

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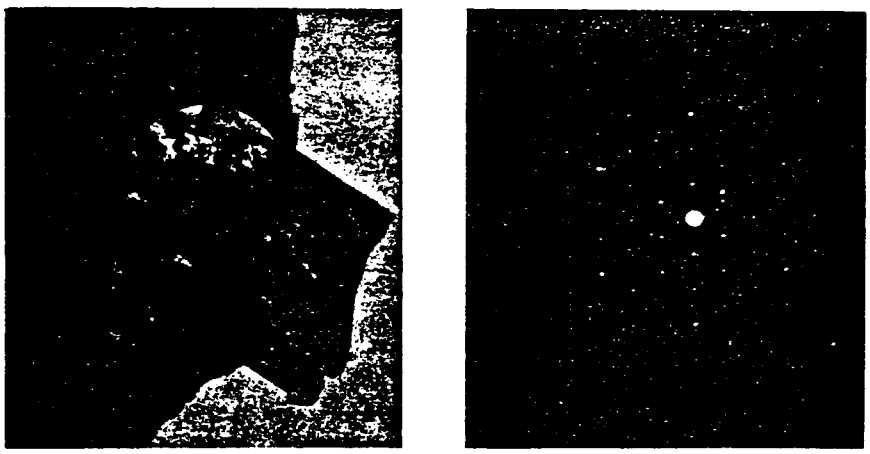


FIGURE 10. Electron micrograph and diffraction pattern of lizardite, from Cornwall, England. (568-22-2) Magnification = 21,000 X.

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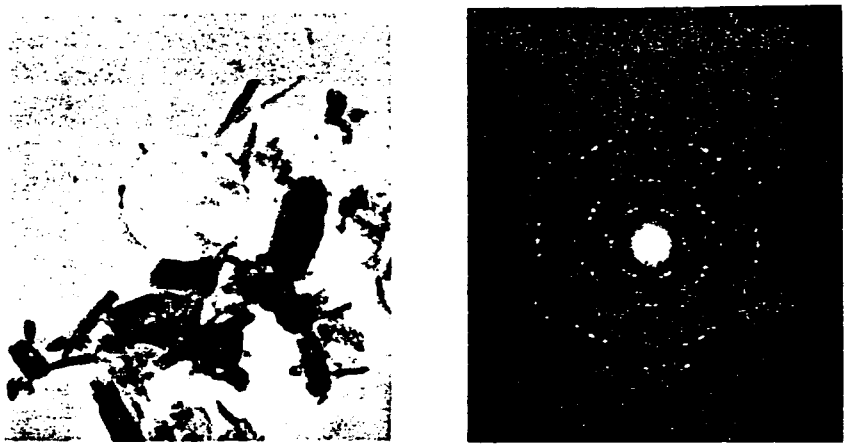


FIGURE 11. Electron micrograph and diffraction pattern of lizardite from Snarum, Norway. (568-22-1)
Magnification = 21,000 X.

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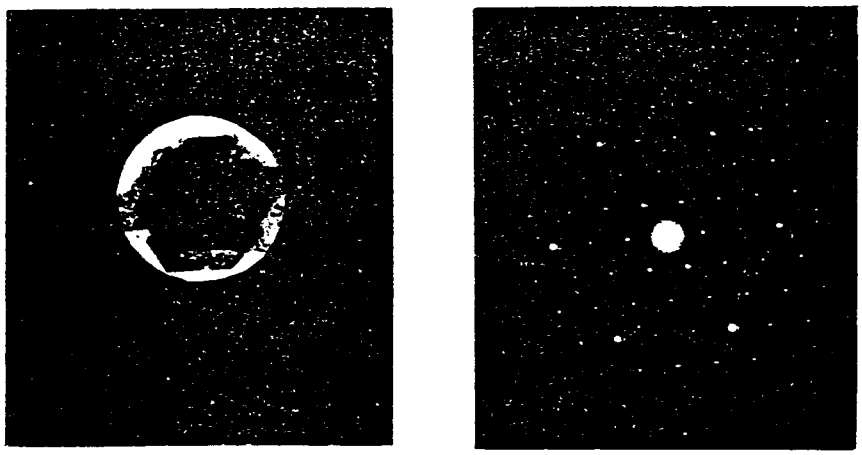


FIGURE 12. Electron micrograph and diffraction pattern of lizardite from the Coalinga asbestos deposit, in antigorite from Santa Rita Peak. (487-52-8) Magnification = 21,000 X.

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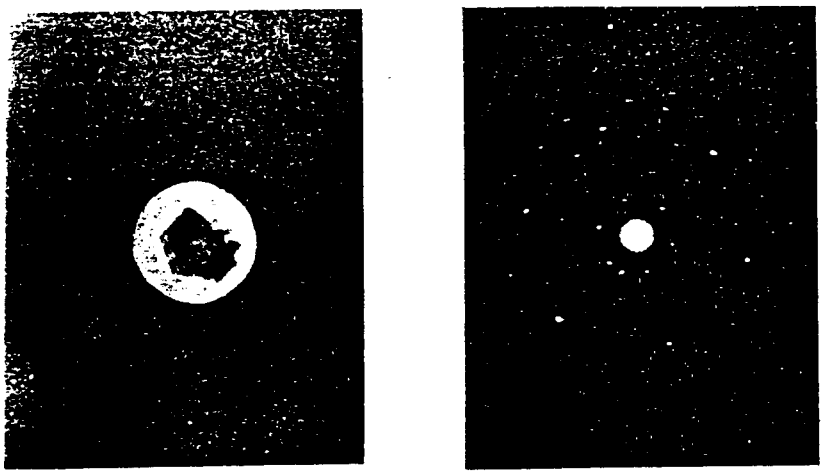


FIGURE 13. Electron micrograph and diffraction pattern of lizardite in antigorite sample from Val Antigorio, Italy. (367-2-2) Magnification = 21,000 X.

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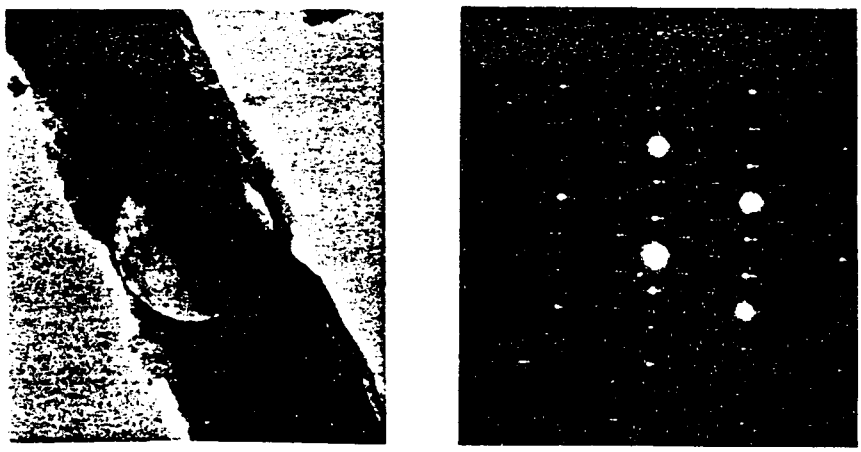


FIGURE 14. Electron micrograph and diffraction pattern of antigorite from Santa Rita Peak, Coalinga asbestos deposit. (487-52-8)
Magnification = 21,000 X.

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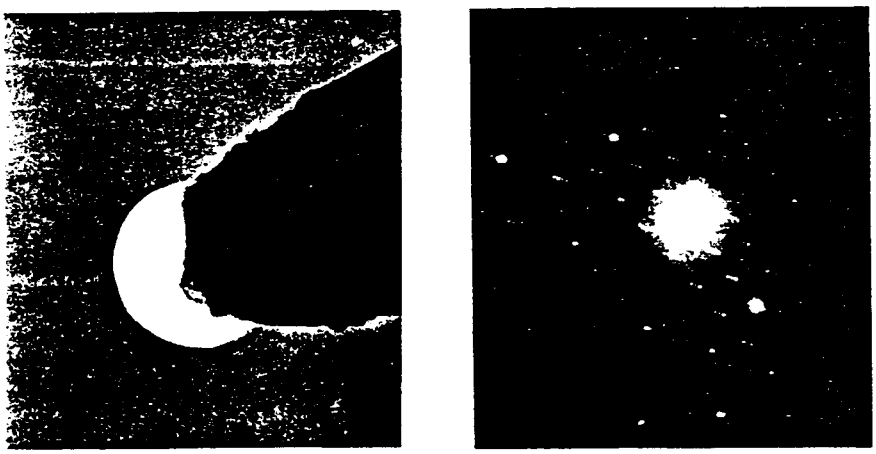


FIGURE 15. Electron micrograph and diffraction pattern of antigorite from Val Antigorio, Italy. (367-2-2)
Magnification = 21,000 X.

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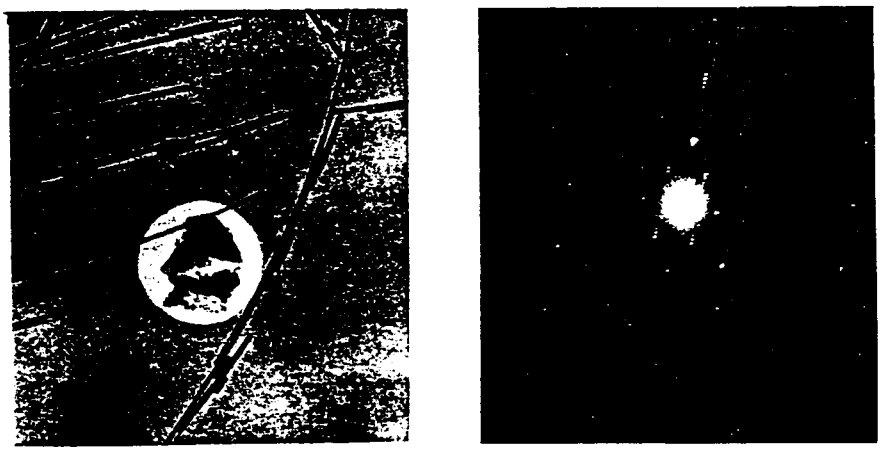


FIGURE 16. Electron micrograph and diffraction pattern of antigorite from Val Antigorio, Italy with chrysotile. (367-2-2) Magnification = 21,000 X.

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An important conclusion, aside from a means of identification, that can be drawn from electron-diffraction studies of serpentine specimens is that absolutely monominerallic assemblages are a rarity and may not exist at all. In all specimens examined, including type materials, at least two polymorphs were found coexisting, and all combinations of lizardite, chrysotile, and antigorite have been observed. The actual amounts of the impurity phases are quite small in some cases and, for all practical purposes, a specimen may be called monominerallic. In any case, impurities of less than about two percent do not appear to affect the results of other analyses, such as X-ray diffraction, DTA, etc.

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GEOLOGIC ENVIRONMENT OF THE DEPOSIT

REGIONAL GEOLOGY

The New Idria serpentinite has been described in detail by several authors and has been the scene of several mining operations for such materials as chromite, magnesite, and benitoite gem stones. Since 1858, more than one-half million flasks of mercury have been produced from the New Idria Mine, one of the largest producers of mercury in this country. The geologic map of the serpentinite area, prepared by Eckel and Meyers (1946) and modified by Coleman (1957), is shown in Figure 17. The area is located almost equidistant between the Great Valley of California on the east and the San Andreas fault zone on the west, at the southern end of the Diablo Range. The serpentinite takes the form of an elongate oval, flanked by upturned sediments of the Franciscan formation of Jurassic age and of the Cretaceous Panoche formation. It resembles an asymmetric dome lying along the northwest extension of the Coalinga anticline, and forms resistant ridges surrounded by lower, rounded hills. Most of the contacts between the serpentinite and the enclosing sedimentary rocks are covered by landslides; however, where a contact is visible it is often steeply dipping and is marked by high angle faults or zones of extensive shearing. Little evidence has been found of contact metamorphic phenomena and it is likely that the present position of the serpentinite is the result of

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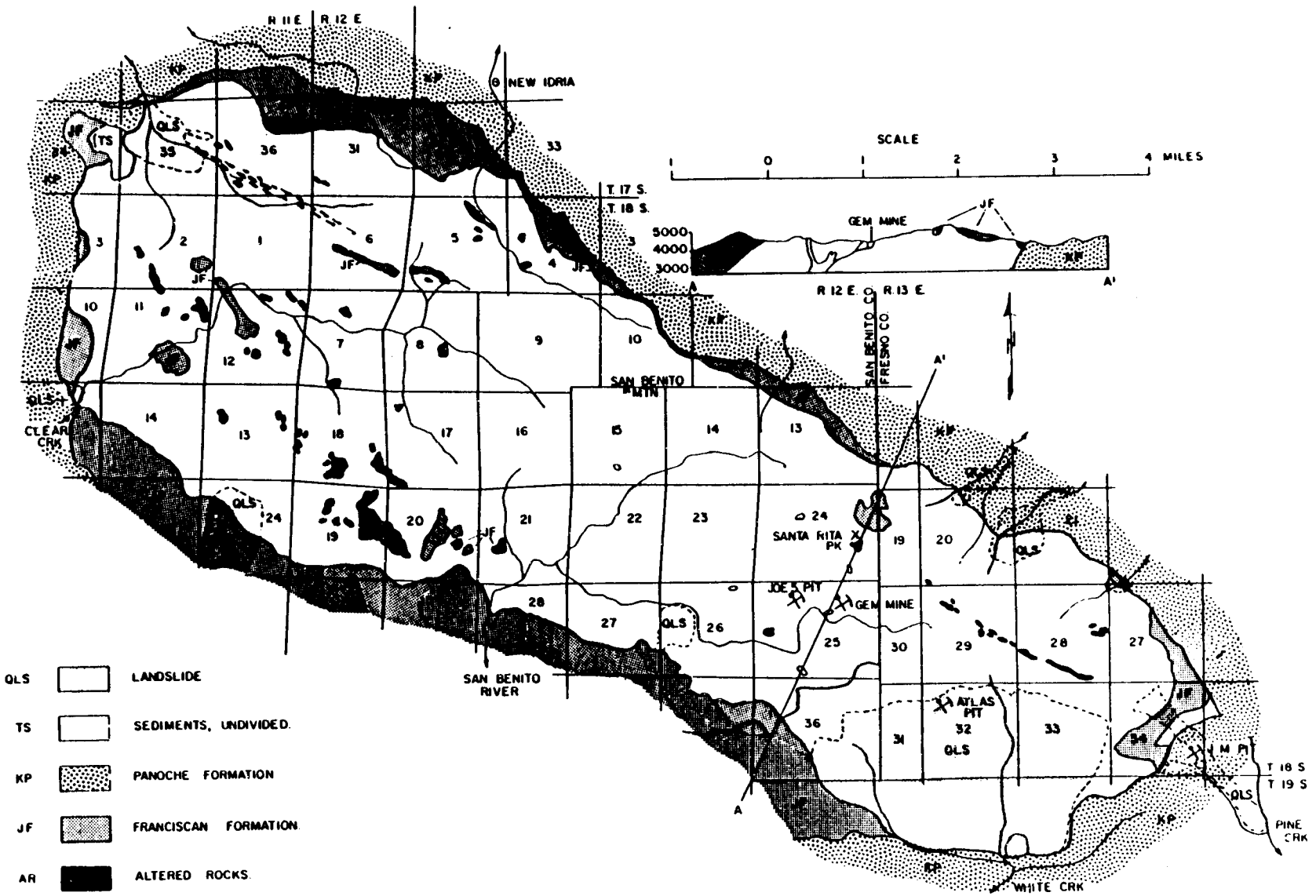


FIGURE 17. Geologic map of the New Idria serpentinite. (from Eckel and Meyers, 1946 as modified by Coleman, 1957)

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tectonic forces rather than of magmatic intrusions (Coleman, 1957, p. 10).

The Franciscan sediments are mostly greywacke sandstones and form a discontinuous rim around the serpentinite. Coleman (1957) has described a number of isolated patches of glaucophane schists along the border between the serpentinite and the Franciscan rocks and attributes their presence to tectonic metamorphic forces that accompanied the intrusion of the serpentinite. Only fault contacts between the Franciscan formation and the serpentinite have been observed. Inclusions of material similar to the Franciscan sediments within the serpentinite probably represent xenolithic fragments caught up in the serpentinite during its emplacement. These bodies are usually only a few hundred square yards in size. Many have been transformed into glaucophane-albite schists, similar to the metamorphosed peripheral rocks discussed above. Several low-pressure jadeite occurrences have been found within the serpentinite in what also appears to be metamorphosed Franciscan material. One such occurrence is located only a few hundred feet west of Santa Rita Peak, well within the main asbestos area of the serpentinite.

Surrounding the Franciscan rocks, and in some places directly in contact with the serpentinite, are rocks of the Panoche formation. Here also only fault contacts have been observed between the Panoche formation and the much older Jurassic sandstones, suggesting that the Franciscan formation has also been tectonically

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displaced upwards along with the serpentinite itself. In several places Panoche shales and sandstones have been found to contain small chips of serpentine, indicating that the serpentinite body was already uplifted and undergoing erosion during Cretaceous time.

GEOLOGY OF SERPENTINITE

The New Idria serpentinite occupies an area about 4 miles wide and 12 miles long and is made up almost entirely of minerals of the serpentine group. According to Coleman (1957), the serpentinite is a low temperature alteration product of a pre-existing ultrabasic igneous rock, although only meager evidence of the original dunite or peridotite rock can be found today. He states further that "The most important feature of the serpentine is the completeness of the serpentinization...," and indicates that the parent olivine-rich assemblage was completely altered to serpentine far beneath the surface. The resultant serpentinite mass was then injected "cold" into the overlying sediments by tectonic forces. Although typical mesh-type textures, pseudomorphous after olivine, have been observed in thin sections of the serpentinite, few grains of relict olivine itself have actually been detected. A number of narrow bands of pyroxene have been encountered, but the over-all textural characteristics of the serpentinite suggest that pyroxene was not a major constituent of the original igneous rock (Coleman, 1957, p. 99). The presence of significant quantities of brucite in the serpentinite, not detected by Coleman, also indicates that the parent

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ultrabasic rock was a dunite rather than a peridotite. These relations will be discussed at greater length in the section dealing with the origin of the serpentinite.

The physical appearance of the New Idria serpentinite actually bears little resemblance to most of the other serpentinite bodies found throughout the world, since the great bulk of the mass has been highly sheared and pulverized, and consists of soft, friable sheets and clumps of asbestoform material admixed with a fine, talcose, asbestos powder. The friable serpentinite has little strength or coherence and crumbles with a touch. Veins of cross-fiber chrysotile, detected in only two localities at the extreme ends of the body, at or near the contacts, may be the products of localized hydrothermal alterations. Hard, dense, competent masses of serpentinite, varying in size from fractions of an inch to boxcar dimensions, are scattered throughout the body and stand out as resistant knobs or ridges. Many are rounded and take the shape of residual "boulders," encased in softer, friable material.

A most pronounced feature of the body is the extensive shearing which has taken place with myriads of fractures and joints crisscrossing the serpentinite. This phenomenon is most noticeable in the southeastern part of the body, coinciding with the areas of highest grade asbestos. In the northwestern part of the body, large masses of residual serpentinite are much more widespread and the quantity of soft friable asbestos is greatly diminished. A view of

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one of the high-grade areas of the New Idria serpentinite showing typical, white, asbestos-strewn slopes is shown in Figure 18. In certain parts of the deposit, hard chips of green-bladed chrysotile cover barren slopes, as seen in Figure 19.

The total thickness of the serpentinite and of the asbestos ore is not known; however, gravity surveys of the area indicate that the body extends to a depth of approximately 15,000 feet (Byerly, 1954, p. 48). Drill holes located in the NW 1/4 of section 25, T18S, R12E, collared at an elevation of 4215 ft. and near the New Idria Mine reservoir in section 32, T17S, R12E and collared at 3780 ft. penetrated serpentinite to a depth of nearly 500 ft.

In addition to isolated patches of metamorphosed Franciscan sandstone scattered throughout the serpentinite, a number of small igneous stocks have been observed and have been classified by Coleman (1957) as silica-deficient syenites, albitites and camptonites. Metasomatic calcsilicate and titanosilicate bodies formed by the direct replacement of serpentine are also present throughout the body and are thought by Coleman (1957) to be the result of hydrothermal solutions emanating from independent igneous sources, rather than to have formed by the same processes responsible for the serpentinization itself. Lenses and bands of silica-carbonate rocks are abundant in the interior of the serpentinite as well as

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FIGURE 18. White, asbestos-strewn slopes in the central part of the New Idria serpentinite

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FIGURE 19. Barren slopes covered with green-bladed chrysotile, Coalinga asbestos deposit

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along the perimeter of the mass. Many occur as resistant dike-like bodies and appear to follow prominent fault zones, and have probably formed from localized hydrothermal alteration of pre-existing serpentine. According to Bright (1959), these rocks are composed of "...chalcedony, quartz, opal, and possibly ankerite" and form tough, porous outcrops. Because of the unusual erosional shapes these materials assume, they are prized by the local inhabitants as rock-garden ornaments, etc.

As mentioned above, the most striking feature of this deposit is the highly sheared and pulverized nature of the serpentinite body itself. Countless episodes of tectonism have produced an asbestos ore which consists essentially of soft, friable agglomerates of short-fiber chrysotile. The ore is remarkably amenable to either dry or wet milling processes, both of which are based upon the separation of the hard, dense fragments of serpentinite rock from soft, friable flakes and fibers. In one way or another, all milling processes tend to remove the rocky fragments, magnetite and dark colored contaminants from the ore, leaving behind a soft, white, high-purity, grit-free asbestos product.

LANDSLIDE PHENOMENA

One of the most interesting features of the geology of the New Idria serpentinite is provided by the numerous landslide areas which cover much of the body. The extremely incompetent nature of the serpentinite, especially when it is wet, and the clay-like

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character of the powdery serpentine have resulted in a material prone to landslide activity. Throughout the serpentinite, slides have filled former valley bottoms and have covered areas as large as several square miles leaving a hummocky-type topography. Many of the slides are still thought to be active, and Figure 20 illustrates the typical crescent-shaped scarp of a landslide in the making, in an area less than a mile from the Joe 5 pit. The mill and mine site of the Coalinga Asbestos Company are both located on a two-mile long slide which flowed from the serpentinite proper down into Pine Canyon (see Figure 17).

The cause of the landslides is not completely understood, although they have been likened to the quick clay landslides of the Ottawa River Valley and of the Göta River Valley in Sweden (Kerr, 1963). The serpentinite is saturated with water at all depths below a few feet and many drill holes have intersected perched water tables at various depths. Heavy rains, coupled with any of the numerous earth tremors which shake the region, may trigger a huge mass of serpentinite, causing it to flow rapidly down a slope, much like a thixotropic liquid changes from a solid to a fluid with rapid stirring.

A serpentine-rich body, known as the Big Blue member of the Temblor formation, occurs interbedded with sediments of late Miocene age in the Big Blue Hills, a few miles north of Coalinga. This material is thought to have originated as a gigantic landslide

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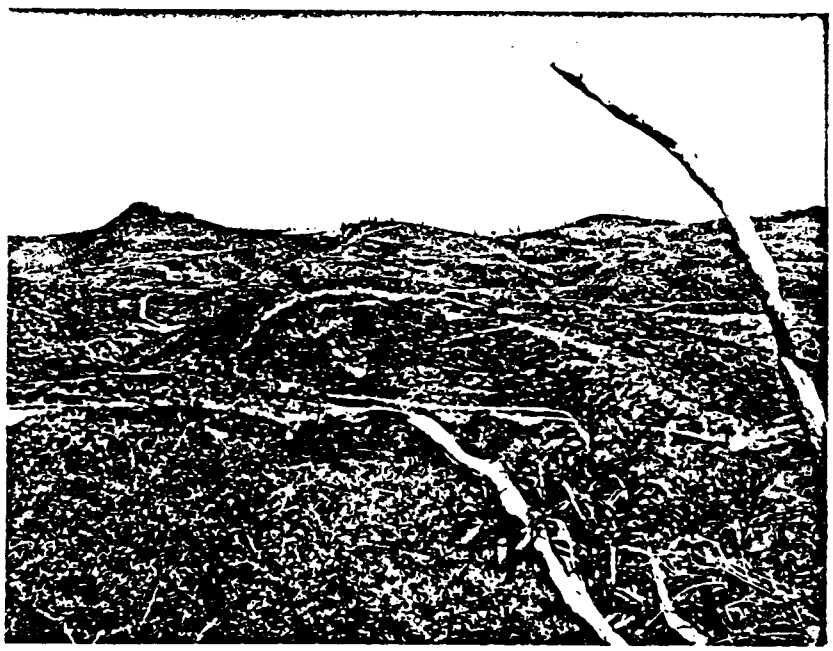


FIGURE 20. Crescent-shaped scarp of landslide, Coalinga asbestos deposit

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from the New Idria serpentinite, the only other serpentinite body in the region. According to Bright (1959), this material consists of serpentine chips and plates, as well as large "boulders" resembling those of the New Idria body. This formation thins away from the New Idria body and has been detected in oil well drill holes as far away as 30 miles. Bright suggests that a sudden uplift of the serpentinite in Miocene time resulted in the rapid erosion and flowing of the serpentine.

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MINERALOGY OF THE FRESH ASBESTOS ORE

The Coalinga asbestos ore is a mixture of several physically different types of serpentine materials, with gradations between the types being the rule rather than the exception. The four main types of material distinguishable in the ore are: (1) hard, dense, dark-blue and green fragments of blocky serpentinite, ranging from fractions of an inch to several tens of feet in diameter; (2) large, tough, leathery sheets of matted chrysotile, resembling mountain leather, which range from several square feet in size; (3) small, brittle, bladed and platy fragments of green serpentine, up to several square inches in size; and (4) soft, friable, greenish-white agglomerates of flaky asbestos, varying from about 1/4" to 1" in diameter, and which contain appreciable quantities of both the green-bladed material and the hard, dense serpentinite rock fragments.

Scattered throughout the soft, friable asbestos ore are large serpentinite "boulders," up to several feet in diameter, which have apparently withstood the intense deformation accompanying the formation of the deposit. The grade of the ore is directly related to the quantity of hard, rocky, serpentinite material present in any given sample. The leathery chrysotile sheets and the green-bladed materials are generally found on the slickensided surfaces of these "boulders" and were probably formed by intense shearing along faults

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and fractures within the rock body. The highly friable nature of the Coalinga asbestos ore is also thought to result from shearing actions which took place during the emplacement of this body and which can be compared with the grinding and milling of hard serpentinite blocks into a semi-plastic asbestos paste.

From the results of X-ray diffraction and electron microscopic examinations, the Coalinga asbestos ore consists predominantly of members of the serpentine group of minerals. Chrysotile, itself, is the major constituent of the soft, friable asbestos agglomerates and is the only phase present in the leathery sheets and the green-bladed serpentine fragments. The hard, dense, serpentinite "boulders" consist primarily of lizardite and antigorite, with varying amounts of very short-fiber chrysotile, brucite, and magnetite. Minor quantities of calcite and traces of chromite and uvarovite garnet are also present. Locally, concentrations of magnesite, diopside and a montmorillonite-like clay mineral have been identified.

Chemically the Coalinga asbestos ore is remarkably homogeneous. Analyses of ten-foot interval composites from drill hole L-11-SF, located near the Joe 5 Pit (see Figure 17) are listed in Table VI. Aside from the surface weathering zone between 0 and 20 feet, few changes in composition are apparent, although the actual fiber content of these samples ranges from 35 to 74%. In general, the magnetite content, as measured by a permeameter technique, is

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TABLE VI. CHEMICAL ANALYSES OF HIGH-GRADE ORE FROM DRILL HOLE L-11SF, COALINGA ASBESTOS DEPOSIT

	0-10'	10-20'	20-30'	30-40'	50-60'	80-90'	110-120'	160-170'
SiO_2	39.59	33.88	36.73	36.75	37.34	36.91	35.68	36.67
MgO	38.20	39.82	39.00	40.76	40.57	40.31	41.15	39.92
FeO	2.16	1.55	1.94	1.98	2.66	2.39	2.46	2.53
Fe_2O_3	6.10	5.44	5.19	5.80	5.06	5.22	4.91	5.14
CaO	0.30	1.02	0.54	0.67	0.56	0.82	0.69	1.00
CO_2	0.43	4.16	1.29	0.82	0.67	0.79	0.70	0.68
H_2O	12.58	14.04	13.88	13.50	13.68	13.47	14.20	13.69
Total	99.36	99.91	98.57	100.28	100.54	99.91	99.79	99.63
Fiber %[1]	-	74	53	63	43	52	35	54
Magnetite[2]	-	4.4	4.8	7.5	4.8	4.4	3.3	4.9

[1] Dispersable fiber by Barbaras (1953) technique

[2] Permeameter measurement

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also fairly consistent from about 4-6%. The magnesia/silica ratios of these samples leave no doubt that brucite is present, a conclusion verified by X-ray diffraction analyses of these same materials.

FRIABLE ASBESTOS ORE

Soft, friable, greenish-white agglomerates make up the bulk of the Coalinga asbestos ore and generally contain over 80% short-fiber chrysotile. When thoroughly dried, these materials break up readily into a soft, fine powder, along with flakes of matted chrysotile and small particles of hard, gritty serpentinite. Several erroneous reports of talc have been recorded in the literature (Anonymous, 1957; Matthews, 1961; Miller, 1960); however, these identifications have not been confirmed, and to date, talc has not been found in any of the several thousand samples examined during this study.

The fibrous nature of the short-fiber chrysotile from the Coalinga deposit is readily apparent under the microscope; however, individual fibers are much too small to be seen by this technique and optical microscopy provides only an equivocal means of identification. The mean indices of refraction, recorded for many samples, are close to the values reported by Deer, Howie and Zussman (1962) for cross-fiber chrysotile. On the other hand, magnetite and other particulate matter in purified fractions of chrysotile are plainly visible in purified fractions of chrysotile, and microscopic techniques provide a reliable means of evaluating asbestos products.

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X-ray diffraction patterns of several chrysotiles, purified from various types of serpentine materials in the Coalinga ore, are listed in Table I and compared with those of other chrysotile samples. These data match well with each other, as well as with those of standard chrysotiles, as listed in Deer, Howie, and Zussman (1962). Although most of the samples examined appear to be the clino-chrysotile variety, no rigorous attempt has been made to differentiate among the several chrysotile polymorphs in this study. Monominerallic specimens of chrysotile are easily identified using powder camera techniques; however, mixtures with lizardite and/or antigorite prove to be much more difficult, and reliable identifications of such materials cannot always be made by this technique.

Chemical analyses of several different types of chrysotile from this ore are listed in Table VII. Although these data yield the approximate composition of Coalinga chrysotile, the actual composition of a particular type of chrysotile in an individual sample cannot be pinpointed exactly. The very processes used in purification, themselves fractionate the sample, and thus yield products biased toward that type of chrysotile which is easily liberated and separated. The composition of this material may be significantly different from that of the very short-fiber material which tenaciously adheres to the gangue materials in the sample, and defies purification. From the analyses of Table VII, it can be seen that the green-bladed chrysotile contains almost twice as much iron as

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TABLE VII. CHEMICAL ANALYSES OF PURIFIED CHRYSOTILE SAMPLES FROM THE COALINGA ASBESTOS DEPOSIT

	Leathery Sheets 367-34-1[1]	Green-Bladed 367-34-2[1]	Cross-fiber 487-52-18[1]	487-27-3-6	287-27-4-6	287-27-2-6	585-90-1	585-90-2	487-27-9-6
SiO_2	41.75	41.42	41.02	38.73	40.25	39.40	39.69	41.92	38.77
Al_2O_3	0.05	0.04	0.31	-	-	-	-	0.36	4.87
Fe_2O_3	1.40	2.05	2.03	1.24	1.13	1.47	1.03	0.99	1.19
FeO	0.27	1.61	2.44	0.39	0.73	1.21	1.02	0.64	0.59
(Fe)	(1.19)	(2.65)							
NiO	0.03	0.07	-	0.25	0.08	0.28	0.07	0.09	0.13
MgO	43.04	43.76	40.44	39.69	40.69	40.71	39.90	41.76	38.71
CaO	-	0.54	0.25	0.21	0.15	0.14	0.16	0.07	0.14
H_2O		13.66	13.30	13.59	13.74	13.85	12.89	13.26	13.85
TOTAL	100.00[2]	100.00[2]	99.79	94.10[3]	96.77[3]	97.06[3]	94.76[3]	98.99	98.25

1) Untreated sample; all others were purified by chemical dispersion techniques and are therefore abnormally rich in alumina. Sample 585-90-2 was chemically dispersed but was washed thoroughly afterwards.

2) Recalculated to 100 per cent after correcting for calcite.

3) Totals reflect the lack of determinations for alumina, probably about 4-5%, as seen in sample 487-27-9-6.

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the leathery sheet material. The cross-fiber sample, however, is even more iron-rich and contains significantly more aluminum.

Surface area measurements by Naumann and Dresher (1966) indicate that the Coalinga chrysotile has a surface area of about 80 M^2/gram, compared with values close to 20-30 M^2/gram for most chrysotile from cross-fiber-type deposits. They attribute the higher values for the Coalinga material to the absence of "solid matter filling the voids between fibrils." It is also interesting to note that chrysotile from the Stragari deposit in Yugoslavia, the only other known deposit having similar characteristics, is also a large surface-area variety (see Miller, 1952; Pavlovic, 1953).

As mentioned above, the most unequivocal means of examining serpentine materials is by electron microscopic and diffraction techniques. Not only may individual grains and fibers be viewed directly, but the characteristic electron diffraction pattern of the various serpentine polymorphs may also be recorded from a single flake or cluster of fibers. The fiber lengths of chrysotile from the Coalinga deposit vary widely from material to material. The longest fibers, measuring several microns in length, generally occur in the leathery sheets and in the flexible platelets of the friable asbestos agglomerates (see Figure 2). Chrysotile from the serpentinite rock fraction of the ore is considerably shorter and thicker than normal, and length/width ratios as small as 10 to 20 are not uncommon (see Figure 3). The short, stubby nature of such materials

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may be the result of inhibited growth within the compact rock masses, compared with the relatively "open" environment in fractures and cracks between serpentinite blocks. Replica electron micrographs of green-bladed chrysotile are shown in Figure 21. Here the highly oriented nature of the chrysotile fibers is readily apparent, and contrasts vividly with the swirling mesh of fibers in the leathery sheet material, as shown in Figures 22 and 23. Chrysotile from green-bladed fragments is also significantly shorter than that from the leathery sheets. Within a single green-bladed grain, the fibers appear to be tightly held in a "whiskbroom" manner, with an occasional fiber peeling off an edge.

The random, disoriented nature of the chrysotile in the leathery sheets, not unlike the arrangement of cellulose fibers in paper, may be the result of the squeezing and drying of a gelatinous chrysotile mass, which fills veins and coats surfaces during the emplacement or the later deformation of the serpentinite body. Materials resembling the green-bladed chrysotile are not uncommon in serpentinite bodies and are often referred to as "picrolite." This term, however, is more correctly applied as a textural term, referring to fibrous varieties of antigorite (Deer, Howie and Zussman, 1962, p. 174), and should not be used for materials from the Coalinga deposit.

In addition to chrysotile, small quantities of the platy serpentines, brucite, and magnetite are also present in the friable

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may be the result of inhibited growth within the compact rock masses, compared with the relatively "open" environment in fractures and cracks between serpentinite blocks. Replica electron micrographs of green-bladed chrysotile are shown in Figure 21. Here the highly oriented nature of the chrysotile fibers is readily apparent, and contrasts vividly with the swirling mesh of fibers in the leathery sheet material, as shown in Figures 22 and 23. Chrysotile from green-bladed fragments is also significantly shorter than that from the leathery sheets. Within a single green-bladed grain, the fibers appear to be tightly held in a "whiskbroom" manner, with an occasional fiber peeling off an edge.

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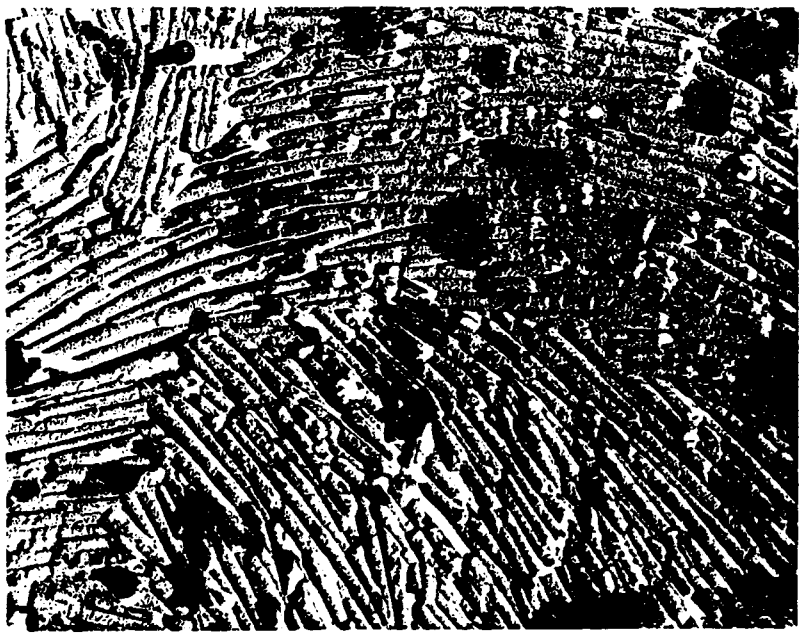


FIGURE 21. Electron micrograph of a replica of chrysotile from green-bladed fragments from the Coalinga asbestos deposit. Magnification = 47,000 X.

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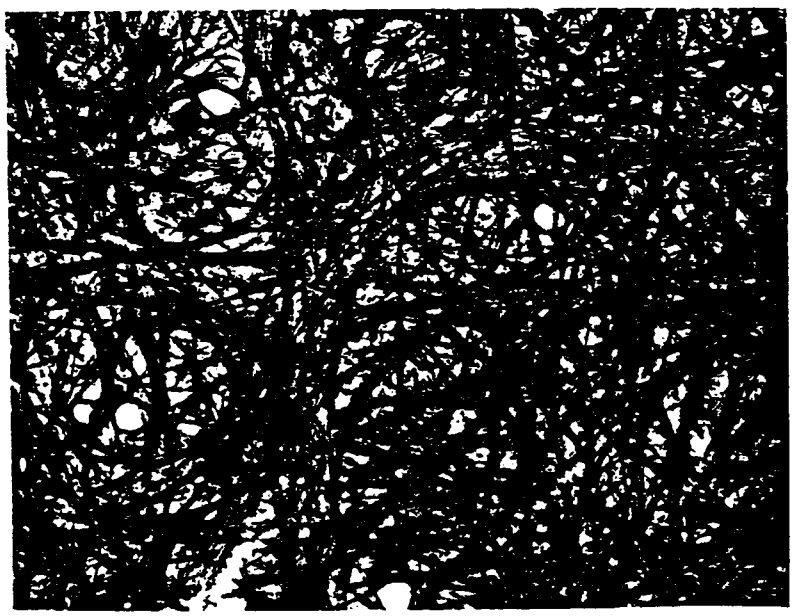


FIGURE 22. Electron micrograph of a replica of chrysotile from leathery sheets from the Coalinga asbestos deposit. Magnification = 20,000 X.

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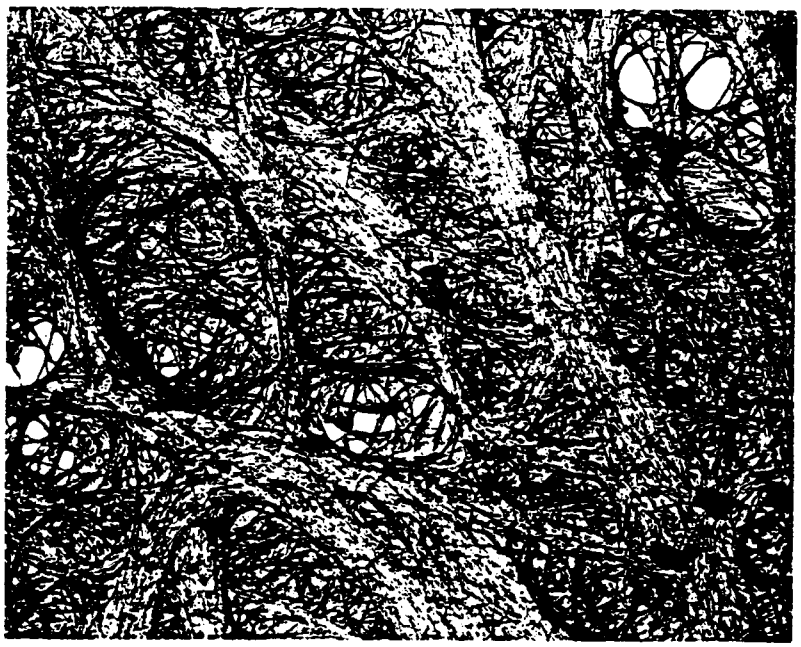


FIGURE 23. Electron micrograph of a replica of chrysotile from leathery sheets from the Coalinga asbestos deposit. Magnification = 5000 X.

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portion of the fresh asbestos ore; however, these phases occur primarily in the tiny fragments of the hard serpentinite rock which are caught up in the soft, flaky material. Their occurrence will be discussed in more detail in the following section. Of special importance, however, is the manner in which small flakes of leathery chrysotile completely enclose, in a sandwich manner, harder plates of green-bladed material and fragments of serpentinite. The green-bladed material inside the soft packets is itself significantly softer and more pliable than the larger plates found elsewhere. The soft, chrysotile flakes also enclose aggregates of white calcite, the age of which relative to the asbestos is not precisely known. In places, large flakes and pellets of what appears to be secondary brucite, have also been noted, associated with the soft, chrysotile agglomerates. Magnetite is also scattered throughout the sheets and embedded in flakes of chrysotile, and many of the asbestos agglomerates can be picked up easily with a hand magnet.

SERPENTINITE ROCK FRAGMENTS

The second-most abundant materials in the Coalinga asbestos ore are the hard, dense fragments of residual serpentinite. These rock fragments vary in size from fractions of an inch to several tens of feet in diameter and are generally surrounded by softer, friable asbestos material. They represent remnants of the original serpentinite body which have apparently withstood the intense deformation and tectonic actions which have sheared and pulverized the body

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since its formation. This type of material makes up the major portion of the gangue minerals in the ore and must be separated during milling in order to produce a clean, white, grit-free asbestos product. Although several hundred samples of this material have been examined in one way or another during the course of this investigation, twelve hand specimens, collected from different parts of the deposit, have been studied in detail by petrographic, X-ray diffraction, electron microscopic, electron diffraction and thermal techniques, the results of which are thought to be indicative of the serpentinite as a whole.

Petrographically, serpentinite fragments from the Coalinga body are similar to most serpentinites from around the world. They consist primarily of dense aggregates of serpentine minerals, arranged in a breccia-like manner, as shown in Figure 24. Randomly oriented aggregates of serpentine having shadowy extinction and fibrolamellar structure range in size from 0.05 to 1.0 mm, and often form so-called "mesh" structures, pseudomorphous after parent olivine grains (see Figure 25). In thin sections, the serpentine is colorless. From grain studies, mean indices of refraction between 1.52 and 1.56 have been determined. The laths of "fibers" of serpentine are length slow and the maximum birefringence color observed has been a first order yellow. In many specimens veinlets, up to 0.1 mm wide, and having parallel orientation and extinction, cut across massive serpentine, and may be monominerallic chrysotile. This material

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FIGURE 24. Photomicrograph of a thin section of Sample 487-44-6, showing chrysotile (bluish-gray), brucite probably iron-rich, (brownish-pink), and magnetite (black).
Polarized light.
Magnification 50 X.

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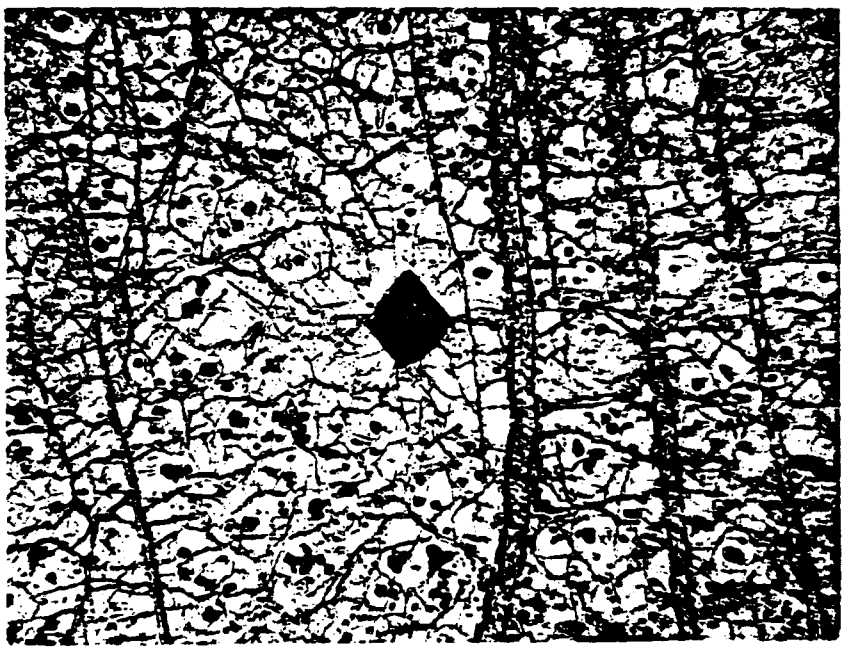


FIGURE 25. Photomicrograph of a thin section of Sample 487-44-9, showing serpentine (white-gray) with characteristic mesh structure and magnetite (black). Non-polarized light. Magnification 50 X.

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is not cross-fiber chrysotile, in the usual sense of the word.

Brucite is also abundant in most serpentinite specimens from this body and forms scaly aggregates from 0.1 to several millimeters in size. Frequently brucite and serpentine are intergrown, forming structures in which thin lamellae of each mineral alternate with one another, as shown in Figure 26. This structure may also be pseudomorphous after parent olivine. Brucite is colorless in thin section, but has a characteristic pinkish-yellow interference color which is diagnostic of this phase in the Coalinga ore. From grain studies, brucite has an index of refraction between 1.57 and 1.58; it is optically (+), and interference figures occasionally show anomalous colors. As seen in Figures 24-26, brucite is frequently found in veinlets with magnetite, which are undoubtedly younger than the bulk of the serpentinite specimen, and were probably formed during post-serpentinization deformation (see also Figure 27). Subhedral grains of magnetite have been observed in all specimens examined and is frequently associated with calcite and veinlets of brucite. Figure 28 shows such an association, with the outer edge and center of the vein consisting of brucite, and chrysotile (?) and fine grained magnetite making up the two inner zones. Dispersed magnetite varies from 0.01 to 1.0 mm in size. The two size ranges shown in Figures 25 and 28 probably represent two generations of crystallization. The larger size particles are probably primary and crystallized along with the olivine from the original dunitic magma,

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FIGURE 26. Photomicrograph of a thin section of Sample 487-44-6, showing chrysotile (bluish-gray), brucite (pink) and magnetite (black). Polarized light. Magnification 50 X.

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FIGURE 27. Photomicrograph of a thin section of Sample 487-52-1, serpentinite from the Joe 5 Pit, Coalinga asbestos deposit. Note the vein of brucite and magnetite, with magnetite coating the vein walls and brucite filling the center portion. Crossed nicols. Magnification = 85 X.

HT-1298

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FIGURE 28. Photomicrograph of a thin section of Sample 487-44-9, showing chrysotile with magnetite (black) and a veinlet as shown in Figure 27.
Polarized light.
Magnification = 140 X.

HT-1299

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while the smaller particles were probably formed during the serpentinization process and represent iron which exsolved from the olivine during its transformation to serpentine and brucite. The average magnetite content of the whole ore is between 4 and 6 weight per cent, as measured by magnetic susceptibility apparatus, with many serpentinite fragments ranging as high as 15 and 20%.

Calcite is common in most specimens and frequently is found in veinlets with magnetite and brucite. It is usually very fine grained, about 0.05 mm in size, and may either represent the recrystallization of primary calcium originally present in the olivine or pyroxene structures, or it may have been formed from calcareous ground waters which permeate the mass. Chromite is present in most specimens and commonly is rimmed by either calcite or magnetite. It is much less abundant than magnetite and forms subhedral grains about 0.5 to 2.0 mm in size. It is characterized by a translucent, dark brown color at the edges of otherwise opaque grains. A chromite grain surrounded by a rim of magnetite is shown in Figure 29. Uvarovite garnet has also been noted in many samples, usually associated with chromite or in the veins cutting the serpentinite. Hostetler, Coleman, Mumpton and Evans (1966) reported trace amounts of awaruite ($FeNi_3$) and heazelwoodite (Ni_3S_2) in one sample from the New Idria body by electron probe analyses.

Two specimens examined in this study were found to contain large quantities of relict olivine, occurring in grains between 0.05

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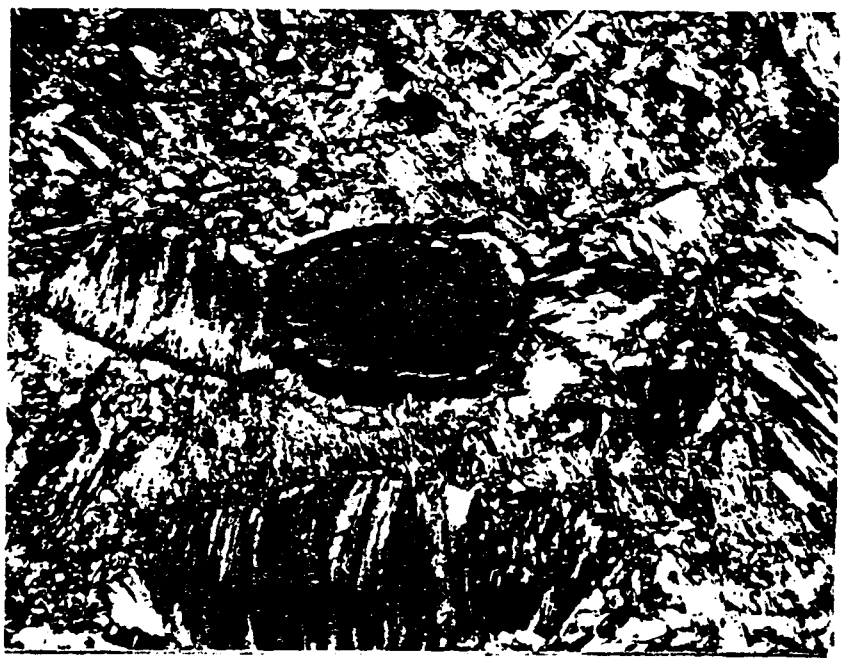


FIGURE 29. Photomicrograph of a thin section of Sample 487-44-6, showing fibrolamellar structure of chrysotile with an inclusion. Center of inclusion consists of chromite (black) which is surrounded by a zone of carbonates (gray-white) and finally a zone of magnetite (black). Polarized light. Magnification = 150 X.

HT-1300

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and 0.10 mm in size, and displaying the typical high relief and interference colors of forsterite (see Figures 30 and 31). In many parts of the thin sections, olivine grains were in optical continuity, undoubtedly relicts of larger, pre-existing olivine grains varying in size from 0.25 to 1.50 mm. The euhedral nature of these pre-existing crystals is apparent in Figure 31. Optical studies by H. W. Jaffe on crushed grains are listed below:

Indices of Refraction	Calculated Mole Percent Fe_2SiO_4
α = 1.652 all = 0.0005	9.5
β = 1.668	8.5
γ = 1.685	7.5

Biaxial (+), 2V = 88° (Calculated from indices of refraction)

Using the curves of Poldervaart, as presented by Wahlstrom (1955, p. 204) an empirical formula of $(Mg_{1.82}Fe_{0.18})SiO_4$ has been derived, in which the olivine has an iron content of 8.8 weight per cent FeO. This is similar to most olivines from dunite rocks and matches well with the dunitic olivines described by Hostetler, Coleman, Mumpton and Evans (1966) in their study of the formation of brucite during pervasive serpentinization of Alpine ultramafics. Relict olivine has only rarely been observed in the New Idria body, testifying to the completeness of the serpentinization process.

The results of electron microscopic and X-ray diffraction studies indicate that both antigorite and lizardite are major constituents of serpentinite rock material of the Coalinga deposit.

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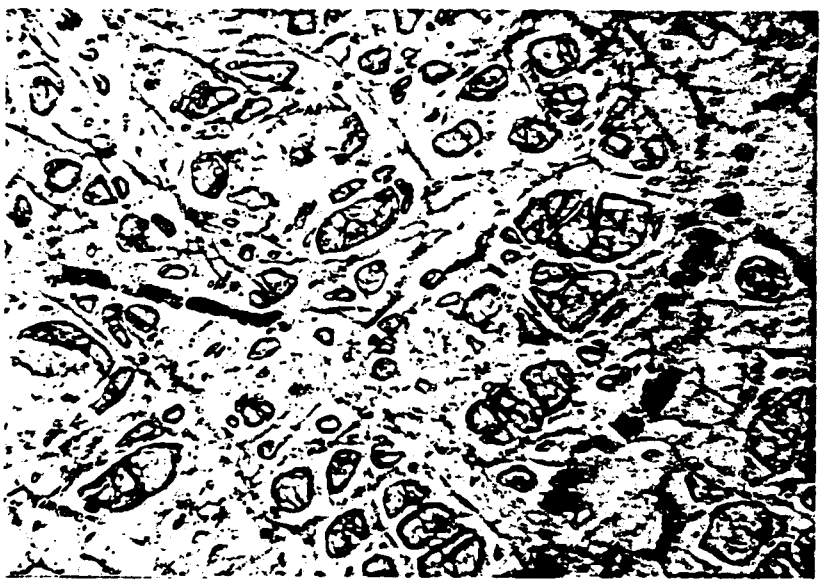


FIGURE 30. Photomicrograph of olivine $(Mg_{1.82}Fe_{0.18})SiO_4$ in serpentine from Sample 487-44-28.
Plane polarized light.
Magnification = 130 X.

HT-1301

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FIGURE 31. Photomicrograph of a large relict olivine grain in serpentine, from Sample 487-44-28.
Plane polarized light.
Magnification = 130 X.

HT-1302

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Varying amounts of short-fiber chrysotile are also present as are minor quantities of brucite and magnetite. X-ray diffraction patterns of the twelve samples studied in detail are listed in Table VIII. The interpretations of both the X-ray diffraction and the electron diffraction data have been made in light of the procedures discussed in the Serpentine Classification Section above. The present authors are in complete agreement with Brindley (1961, p. 94), who states that "Very careful X-ray identification, aided by electron diffraction and electron microscope studies, is essential for a detailed study of these minerals and if impurities or mixtures are present"... precise identification may be impossible." For this reason, identifications of the serpentine polymorphs based on each of the several techniques employed are listed together in Table IX. From electron microscopy, the non-fibrous polymorphs of serpentine are present in a variety of shapes ranging from completely anhedral to euhedral. In many cases, polycrystalline aggregates are present, which even the rigorous preparation procedures of electron microscopy failed to disperse. Although the results of X-ray diffraction and electron microscopy are in good agreement in most cases, the failure to recognize one or more of the polymorphs present in certain samples emphasizes again that no one technique is by itself sufficient for an unequivocal identification of serpentines. Differential thermal analysis diagrams of a number of serpentinite samples are shown in Figure 32. Faust and Fahey (1962) showed that antigorite could

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TABLE VIII

FILM X-RAY DIFFRACTION DATA OF SERPENTINITE SAMPLES FROM THE COALINGA ASBESTOS DEPOSIT

487-44-6		487-44-13		487-44-14		487-44-19		487-44-26		487-52-1		487-44-9		487-52-7		487-52-7-1	
"d"	I/I_o	"d"	I/I_o	"d"	I/I_o	"d"	I/I_o	"d"	I/I_o	"d"	I/I_o	"d"	I/I_o	"d"	I/I_o	"d"	I/I_o
7.25	10+	7.28	10+	7.27	10+	7.27	10+	7.27	10+	7.32	10+	7.31	10+	7.28	10+	7.25	10+
4.76	1	-	-	-	-	4.81	2	-	-	4.77	3	-	-	4.76	5	-	-
4.60	2	4.61	4	4.60	2	4.60	2	4.59	4	4.60	2	4.55	4	4.55	1	4.64	3
4.29	1	4.30	2	4.24	<1	4.26	3	-	-	-	-	-	-	-	-	4.24	4
3.62	9	3.63	9	3.61	9	3.63	8	3.69	10	3.64	10	3.65	10	3.62	7	3.62	10
-	-	-	-	-	-	-	-	3.34	<1	-	-	-	-	-	-	-	-
3.04	<1	-	-	-	-	-	-	3.23	2	-	-	-	-	-	-	-	-
2.96	1	2.96	1	2.96	1	3.01	4	2.99	5	2.97	2	-	-	2.96	2	3.00	1
-	-	-	-	-	-	-	-	2.88	2	-	-	-	-	-	-	-	-
-	-	2.69	1	-	-	2.69	4	2.66	1B	-	-	-	-	-	-	2.69	2
-	-	-	-	2.58	<1	2.58	<1	-	-	2.61	<1	2.60	<1	-	-	-	-
2.52	10	2.52	10	2.52	10	2.52	10	2.50	9	2.53	8	2.50	4	2.53	10	2.52	9
2.46		2.45	<1	2.45	<1	2.46	4	-	-	-	-	2.45	<1	2.44	<1	2.45	<1
-	-	2.41	<1	2.44	2	-	-	-	-	2.42	<1	-	-	-	-	-	-
2.37	2	-	-	-	-	2.37	5	-	-	2.37	4	-	-	2.37	9	2.36	3
-	-	-	-	-	-	-	-	2.30	1	-	-	-	-	-	-	-	-
2.21	<1	2.21	<1	-	-	2.20	<1	2.21	1	-	-	2.22	<1	2.15	<1	2.16	2
2.10	1	2.09	1	2.09	1	2.10	1	2.10	<1	2.10	3	2.09	<1	2.10	1	2.10	<1
-	-	-	-	-	-	-	-	2.04	1	-	-	-	-	2.04	<1	-	-
-	-	2.00	<1	2.00	<1	-	-	2.01	1	-	-	-	-	-	-	1.854	<1
-	-	1.957	<1	-	-	1.955	2	1.959	<1	-	-	-	-	-	-		<1
-	-	-	-	-	-	1.905	1	-	-	-	-	-	-	-	-	-	-
-	-	1.819	1	1.823	<1	1.831	1	1.828	1	-	-	-	-	-	-	-	-
1.788	2	1.781	<1	1.778	<1	1.789	3B	1.785	1	1.792	1	-	-	1.792	4	1.787	<1
1.748	<1	1.746	<1	1.742	<1	1.739	1	1.751	1	-	-	1.735	<1	-	-	-	-
1.711	<1	1.712	1	1.709	<1	-	-	-	-	1.713	<1	-	-	1.713	<1	1.713	<1
-	-	1.668	<1	-	-	1.671	2	1.672	<1	-	-	-	-	-	-	1.671	<1
1.614	2	1.611	2	1.612	2	1.613	4	1.623	2	1.615	3	-	-	1.614	2	1.610	2
1.575		-	-	-	-	1.578	<1	-	-	1.575	<1	-	-	1.577	2	-	-
1.556	4	1.555	4	1.558	2	1.558	2	1.544	5B	1.543	8B	1.541	4B	-	-	1.559	4
1.538	3	1.537	1	1.537	3	1.537	3	-	-	-	-	-	-	1.538	2B	1.537	4
-	-	1.515	1	1.504	1	1.504	2	1.504	3	-	-	-	-	-	-	1.510	<1
1.484	2	1.481	2	1.481	2	1.485	1	-	-	1.484	3	1.467	<1	1.484	2	1.484	<1
1.418	<1	1.417	<1	1.416	<1	1.416	<1	1.423	1	-	-	-	-	-	-	-	-
-	-	1.392	<1	-	-	-	-	1.407	1	-	-	-	-	-	-	-	-
1.374	<1	-	-	-	-	1.371	1	-	-	-	-	-	-	1.369	1	-	-
-	-	-	-	-	-	1.347	1	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	1.328	2	-	-	-	-	-	-	-	-
1.313	3	1.316	3	1.317	1	1.314	3B	1.310	2B	1.315	<1B	1.310	1B	1.314	1B	1.315	3
-	-	-	-	-	-	1.299	<1	-	-	-	-	-	-	-	-	-	-
1.280	<1	1.280	<1	1.278	<1	1.282	1B	1.282	2	1.281	<1	-	-	-	-	-	-
1.263	<1	1.259	<1	-	-	1.262	<1B	1.262	<1	-	-	-	-	-	-	-	-

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TABLE IX. MINERALOGICAL DESCRIPTIONS AND IDENTIFICATIONS OF SERPENTINITE SPECIMENS FROM THE COALINGA ASBESTOS DEPOSIT

SAMPLE NO.	LOCATION AND DESCRIPTION	X-RAY DIFFRACTION IDENTIFICATION[1]	ELECTRON MICROSCOPE & DIFFRACTION IDENTIFICATION	DIFFERENTIAL THERMAL ANALYSIS IDENTIFICATION[2]
487-44-6	Hard, sense, dark green serpentinite from floor of Joe 5 Pit.	Antigorite Brucite s. Magnetite	Chrysotile Antigorite	Chrysotile/Lizardite Antigorite Brucite
487-44-9	Unweathered inner portion of large serpentinite "boulder" in Condor Pit located in Section 29.	Chrysotile Lizardite s. Brucite s. Magnetite	Lizardite Brucite	Chrysotile/Lizardite Brucite
487-52-7	Hard, dense, dark blue serpentinite "boulder" from center of Atlas Pit.	Chrysotile Brucite s. Magnetite	Chrysotile s. Lizardite s. Antigorite	Chrysotile/Lizardite Brucite
487-52-7-1	Blue-black vein cutting sample 487-52-7.	Antigorite s. Magnetite s. Uvarovite	Antigorite trace Chrysotile	
487-52-1	Serpentinite "boulder" from same locality as sample 487-52-7.	Chrysotile Antigorite Brucite s. Magnetite trace Lizardite	Chrysotile Lizardite trace Antigorite	Chrysotile/Lizardite Brucite
487-44-13	Large, reddish colored "boulder" of serpentinite, near Joe 5 Pit.	Antigorite trace Chrysotile s. Lizardite trace Magnetite	Antigorite s. Chrysotile s. Lizardite	Antigorite
487-44-14	Large serpentinite mass near Joe 5 Pit.	Antigorite s. Magnetite	Antigorite Chrysotile	Chrysotile/Lizardite Antigorite
487-44-19	Green serpentinite "boulder" near contact, Section 36.	Antigorite Brucite Uvarovite	Antigorite s. Lizardite s. Chrysotile	Chrysotile/Lizardite Antigorite Brucite
487-52-8	Main serpentinite mass at Santa Rita Peak.	Antigorite s. Magnetite trace Uvarovite	Antigorite	Antigorite trace Chrysotile/Lizardite?

[1] Film methods used (See Table VII) [2] See Figure 32

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Differential Thermal Analysis Patterns Of Coalinga Asbestos Samples

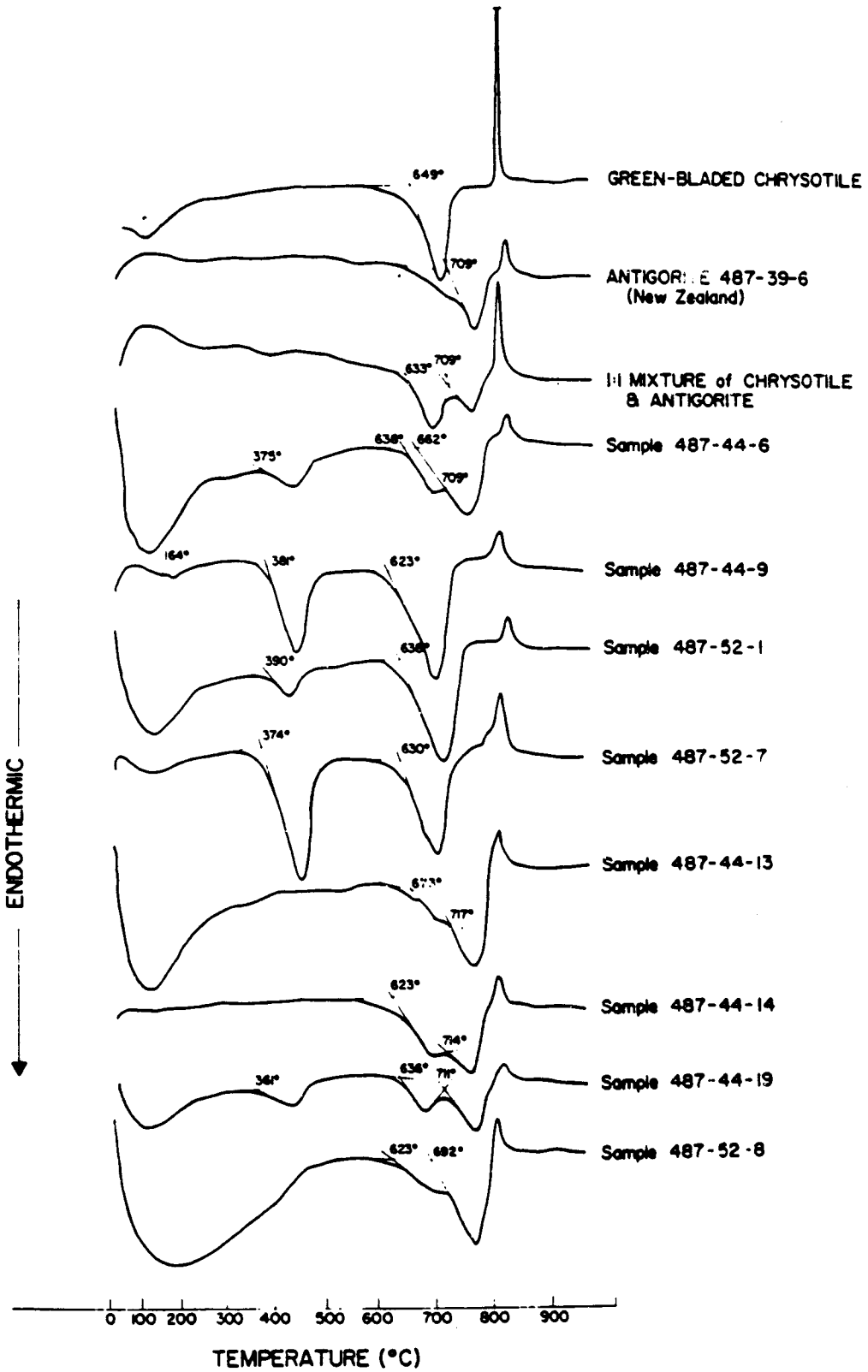


FIGURE 32. Differential Thermal Analyses patterns of serpentinite samples from the Coalinga asbestos deposit.

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easily be distinguished from the pair, chrysotile-lizardite, by this technique, since the former polymorph gave rise to an endothermal peak at considerably higher temperature than either of the other two. Unfortunately, lizardite and chrysotile yield similar D.T.A. patterns, and are therefore indistinguishable by this procedure. In Figure 32, the patterns of pure chrysotile and pure antigorite are compared with that of a 1:1 mixture of the two. The pattern of the mixture shows two distinct endothermal peaks, at widely separated temperatures, while the pure specimens yield only one such peak. As listed in Table IX, the polymorphic composition of the serpentine present, plus the presence or absence of brucite, could easily be confirmed by differential thermal analysis.

Chemical analyses of many of the specimens listed in Table VIII are found in Table X. The main difference to be noted from these data is the wide variation in magnesia/silica ratics which correspond to the presence or absence of brucite in the samples. These data also illustrate the degree of confidence which should be placed on serpentinite genesis discussions based upon chemical analyses of one or two selected specimens from a given serpentinite body.

An unusual form of chrysotile was noted in sample 487-44-6 by electron microscopic techniques, and is shown in Figures 33 and 34. Concentric cylinders of varying diameters appear to be strung along a central chrysotile fiber. Electron diffraction patterns show it to be chrysotile, or more precisely, ortho-chrysotile. The

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TABLE X. CHEMICAL ANALYSES OF SERPENTINITE ROCK SAMPLES FROM THE COALINGA ASBESTOS DEPOSIT

	487-44-6	487-44-9	487-44-14	487-44-19	487-52-8	487-52-1	487-52-7
SiO_2	36.37	30.93	40.26	35.69	40.67	36.45	26.68
MgO	41.28	43.35	38.16	36.74	38.87	40.67	45.85
FeO	2.60	2.51	2.57	2.77	2.35	2.14	6.28
Fe_2O_3	3.46	5.53	5.08	6.26	4.10	5.78	3.00
CaO	0.64	0.15	0.17	3.26	0.23	0.48	0.37
CO_2	0.68	0.77	0.18	0.18	0.07	0.60	0.29
H_2O	12.87	16.96	10.22	11.97	11.02	13.15	17.86
Al_2O_3	0.21		1.45	0.34	0.55	0.24	0.26
Cr_2O_3	0.38		0.32	1.71	0.38	-	-
Total	98.49	100.20	98.41	98.92	98.24	99.51	100.29

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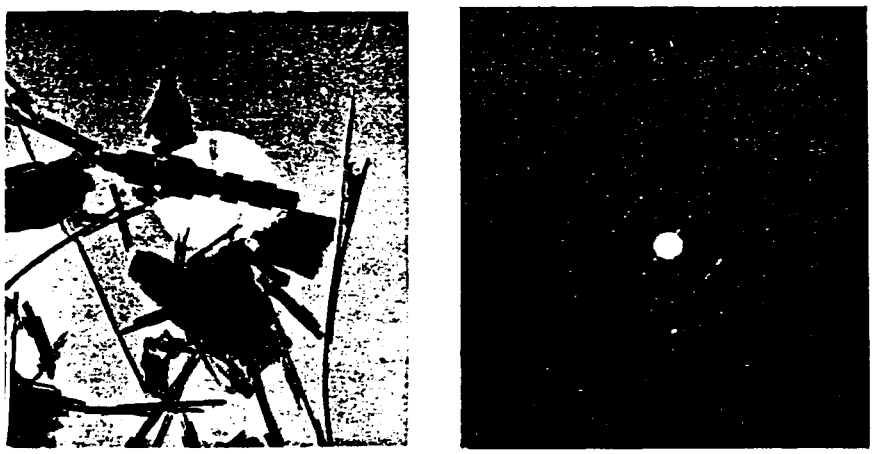


FIGURE 33. Electron micrograph and diffraction pattern of chrysotile in Sample 487-44-6.
Magnification = 20,200 X.
Note the extremely wide tubes of varying diameter.

HT-1303

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FIGURE 34. Electron micrograph of chrysotile in Sample 487-44-6. Note the extremely wide tubes of varying diameter.
Magnification = 41,100 X.

HT-1304

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thickness of the cylinders, from 700 to 3000 Å, is much larger than any values previously reported for chrysotile, although similar materials have been observed in synthetic preparations. The origin of the large diameter chrysotile in the natural sample is unknown at the present time.

BRUCITE IN THE FRESH ASBESTOS ORE

The role of brucite in the New Idria serpentinite is an all important one, from the original emplacement of the body to the final decomposition in the surface weathering zone, and has been discussed in detail by Mumpton and Thompson (1966) and Hostetler, Coleman, Mumpton and Evans (1966). It is present in almost all types of material from this deposit, averaging 7 to 8% in typical ore, and is most abundant in the hard, dense, serpentinite fragments where it commonly comprises from 10 to 25 weight percent of these materials. From the petrographic studies discussed above, it is intimately associated with serpentine, the coexistence of these two phases suggesting strongly that the original ultramafic rock was composed primarily of olivine, with very little pyroxene. As discussed by Mumpton and Thompson (1966), chemical, X-ray diffraction and electron probe data all suggest that most of the brucite from this body is not pure $Mg(OH)_2$, but that it contains approximately 15 weight percent iron in solid solution, with an approximate formula of $(Mg_{10}Fe_2)(OH)_{24}$. The iron content is a critical factor in the susceptibility of the ore to weathering, and exposure of brucite-rich

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ore to surface oxidation conditions invariably leads to marked discoloration. It is interesting to note that many of the large, box-car-size and larger, outcrops of serpentinite are devoid of brucite (i.e., the Santa Rita Peak mass, the large reddish outcrop south of the Joe 5 Pit, samples 487-52-8 and 587-44-13 in Table IX), suggesting that their "longevity" is due to the absence of this phase, which upon weathering would have led to a rapid disintegration (vide infra).

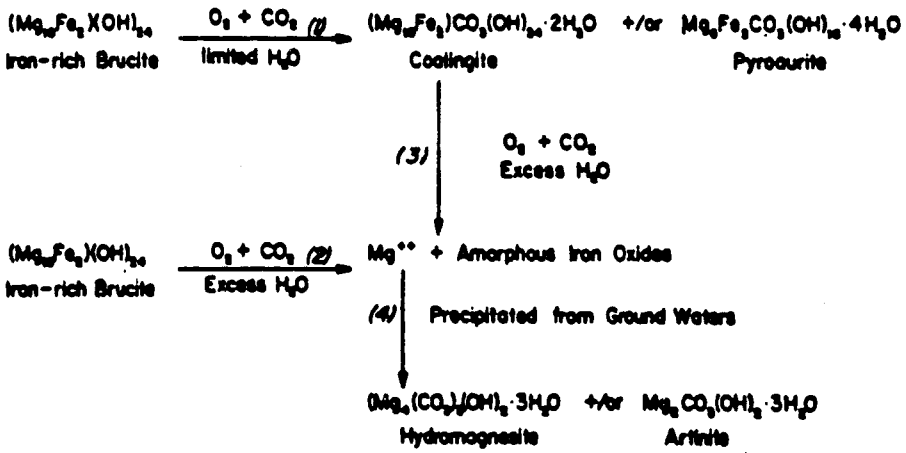
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MINERALOGY OF THE SURFACE WEATHERING ZONE

The mineralogy of the surface weathering zone of the New Idria serpentinite has been studied extensively by Mumpton, Jaffe and Thompson (1965) and Mumpton and Thompson (1966) and need not be discussed at length here. The reddish-brown colored weathering zone extends to a depth of 20-30' and is present throughout the entire deposit. Blocks and fragments of residual serpentinite have been transformed into soft, brown, crumbly masses, while the surrounding friable asbestos ore has only slightly discolored. Surface coatings of artinite and hydromagnesite are also common, the latter mineral occurring as concentrations of white, pea-size concretions immediately above the water table. The weathered serpentinite "boulders" are enriched in pyroaurite and coalingite ($Mg_{10}Fe_2CO_3(OH)_{24}\cdot 2H_2O$), a new mineral discovered during the course of this investigation. Amorphous iron oxides are also abundant in highly weathered material, while brucite is essentially absent. Field observations and laboratory experiments have shown that in the surface weathering zone, iron-rich brucite either dissolves, leaving behind a brown, amorphous residue of iron oxide, or transforms in situ into pyroaurite and/or coalingite by oxidation and carbonation. Further weathering destroys these minerals, leaving behind more iron oxides. The dissolved magnesium later precipitates as hydromagnesite throughout the deposit.

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The generalized reactions involved are shown schematically below:



The artinite from the weathering zone occurs as white encrustations of acicular crystals and as minute tufts of radiating needles on fractures and joints in the serpentinite. It is particularly abundant in the Condor Pit area of the deposit in Section 29. This is only the third reported occurrence of this mineral in the country. The X-ray "d" spacings for this material are essentially the same as those reported by de Wolff (1952). Optical determinations by H. W. Jafee are listed as follows:

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Biaxial (-)	α = 1.488	all = .001	The plane of the optical axis if parallel to the ac plane and is at right angles to b; since b = elongation, all observable extinctions are parallel and the true extinction, zc, cannot be observed.
	β = 1.535		
	γ = 1.557		
2V (Calculated)	= 67°		
$\gamma - \alpha$	= 0.069 (birefringence)		

In several parts of the deposit, weathered material has been found at depths well below the normal weathering zone; some drill holes have intercepted brown-colored, oxidized material as deep as 200 feet below the surface. It is thought that such material has oxidized as a result of surface conditions being brought beneath the surface along faults, large fracture zone, etc. In other places, south of the Atlas Pit area, and near the Johns Manville Pit, alternate layers of fresh and weathered ore have been noted, the results of successive landslides which have brought fresh ore on top of earlier weathered surfaces.

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GENESIS OF THE DEPOSIT

Any consideration of the genesis of the New Idria serpentinite must include speculation not only on the origin of this unusual asbestos-rich deposit, but also on the formation and history of Alpine-type serpentinites in general. Classically, such serpentinite bodies are thought to have formed by the low temperature hydration of pre-existing ultramafic igneous rocks, including dunites and olivine-rich peridotities. According to Bowen and Tuttle (1949), below 400°C., olivine (Mg_2SiO_4) reacts with water to yield a mixture of serpentine and brucite. Turner and Verhoogen (1960, p. 318) assumed, however, from petrographic evidence, that the serpentinization process takes place at constant volume, a concept which can only be accounted for by the removal of copious amounts of both magnesia and silica from the system. In a recent study, Hostetler, Coleman, Mumpton and Evans (1966) found that brucite is a major constituent of many serpentinite bodies of the Circum-Pacific orogenic belts. The presence of brucite in these rocks implies "... a larger volume increase than would result if excess magnesia has been removed in solution." They state further that volume increases up to 40% are conceivable, during the serpentinization process. Since field evidence is generally lacking supporting the migration concept, they conclude that pervasive serpentinization "probably results from incremental additions of water derived

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from the country rocks during the tectonic ascent of the ultramafic mass through the earth's crust." Thus, the serpentinization process may be regarded as the hydration of olivine to produce both serpentine and brucite; the reaction is accompanied by a considerable increase in volume and can be expressed as follows:

$$2\ Mg_2SiO_4 + 3\ H_2O = Mg_3Si_2O_5(OH)_4 + Mg(OH)_2$$

Olivine — Serpentine — Brucite

(281g, 88cc) (54g) (277g, 110 cc) (58g, 23 cc)

These authors further conclude that the "... nearly universal occurrence (of Alpine ultramafics and serpentinites) in and along structural discontinuities suggests that much, or all, of the expansion is accommodated during tectonism." It is not unlikely that the volume increases attending serpentinization processes actually assist in the diapiric ascent of the masses. This process may still be taking place today, accounting for the occurrence of such bodies in topographic highs.

In all likelihood, the New Idria serpentinite body formed in a manner similar to that described above. Mineralogical studies have shown that the abundant serpentinite rock fragments in the deposit consist primarily of minerals of the serpentine group with smaller amounts of magnetitie and iron-rich brucite (7-8 weight per cent) suggesting that the parent ultramafic consisted almost entirely of olivine. Although few relicts of unaltered material have been found throughout the deposit, optical studies of a number of olivine

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grains in thin sections have indicated a composition close to $(Mg_{1\cdot82}Fe_{0\cdot18})SiO_4$, not dissimilar from the olivine of most dunite bodies. Analyses of the serpentine and the brucite from the New Idria deposit indicate that the serpentine contains less iron, and the brucite, more iron, than the parent olivine phase, a fact also brought out by Hostetler, Coleman, Mumpton, and Evans (1966) for these bodies in general.

As mentioned above, the New Idria serpentinite is most unusual in that it does not resemble most of the known serpentinite bodies, but consists of a matrix of soft, powdery, friable asbestos-form material surrounding fragments and blocks of hard, dense serpentinite rock. Only the Stragari deposit in southern Yugoslavia is known to be similar, although recently two more such bodies in Bosnia, Yugoslavia, have been reported. (Stubican, personal communication). According to Coleman (1957) the New Idria mass was probably altered to serpentine far beneath the surface and was injected "cold" into the overlying Franciscan sediments. Its locations, a few miles from the famous San Andreas fault zone, probably account for the enormous shearing which has taken place in the body and it is thought that competent blocks of serpentinite were broken and crushed against one another, much as a thick paste is smeared out and pulverized in a wet ball mill or mix-muller. The pulverized product remains today as the highly friable, soft, asbestos-form material containing variable quantities and sizes of uncrushed rock material.

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Several facts remain to be explained, however. Whereas most serpentinite bodies contain only about 5-10% chrysotile in the form of cross-fiber veins, the New Idria body contains about 75-80% of this phase, none of which is in the form of cross-fibers. While the serpentinite rock fragments contain some chrysotile and most of the brucite, the soft, friable matrix material is nearly all chrysotile with little or no brucite. Thus, if the matrix material is a pulverization product of the serpentinite rock fragments, brucite must have been removed during this process, and the serpentine polymorphs, antigorite and lizardite, changed into chrysotile. The solubility of brucite in ground waters is well known, and it is not unlikely that the intense shearing and fracturing of this body facilitated the removal of this material from the friable matrix chrysotile. The presence of a large magnesite deposit in section 36, T17S, R11E may be a result of the dissolution and reprecipitation of magnesium from the ore at depth. The absence of brucite in areas of intense shearing has also been noted by Hostetler, Coleman, Mumpton, and Evans (1966) in many serpentinite bodies from various locations around the world. The transformation of antigorite or lizardite into chrysotile, however, is still not explained and has not been carried out experimentally. The fact that the platy polymorphs of serpentine have also been synthesized in the laboratory suggests that chrysotile is the only <u>stable</u> polymorph at reasonable temperatures and pressures, and that the intense reworking

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(annealing?) of this serpentinite body by tectonic forces allowed the stable polymorphs to form. Obviously, further experimental and petroligic work remains before definite conclusions can be drawn.

Although the abundance of antigorite in this body is somewhat unusual, in that many such Alpine serpentinites are reported to contain only chrysotile and lizardite, reliable identifications of the serpentine polymorphs present in bulk serpentinite material by modern X-ray diffraction and electron microscopic techniques have been made on only a few such bodies.

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