

## MINERALOGY AND ORIGIN OF THE COALINGA ASBESTOS DEPOSIT

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**Abstract**—Since 1960 asbestos production of the United States has more than tripled, a phenomenon due in large part to the development of the Coalinga asbestos deposit in western California. Although most asbestos ores contain 5–10 per cent chrysotile in the form of cross- or slip-fiber veins within massive serpentinite bodies, no such veins are to be found in the Coalinga deposit despite the fact that it contains more than 50 per cent recoverable chrysotile. The Coalinga ore consists of soft, powdery, pellet-like agglomerates of finely matted chrysotile surrounding blocks and fragments of serpentinite rock. The highly sheared and pulverized nature of the ore favors its exploitation by simple, open-pit mining, and high quality products can be prepared by either wet or dry milling processes.

Four types of serpentine material are distinguishable: (1) hard, dense blocks of serpentinite rock, ranging from fractions of an inch to several tens of feet in diameter; (2) tough, leathery sheets, resembling mountain leather, up to several square feet in size; (3) brittle blades and plates of green serpentine, a few square inches in size; and (4) friable agglomerates of soft, powdery chrysotile containing appreciable amounts of the other three. Chrysotile is the principal component of all the above materials, with the exception of the serpentinite rock which consists mainly of lizardite and/or antigorite, with small amounts of brucite, magnetite, and very short fiber chrysotile. Although chrysotile fibers up to several microns in length are present in the leathery sheets, most Coalinga chrysotile is much shorter and arranged in a swirling mesh or disoriented, tangled fibers, much like cellulose fibers in paper. Fragments of serpentinite gangue are scattered throughout the ore and contain most of the lizardite, antigorite, and brucite. Chemical, electron probe, and X-ray analyses confirm the iron-rich nature of the brucite, a critical factor in the susceptibility of this phase to oxidation in the surface weathering zone. Here brucite either dissolves, leaving behind a residue of brown, amorphous iron oxides, or transforms *in situ* to pyroaurite or coalingite. Dissolved magnesium precipitates as hydromagnesite immediately above the water table throughout the deposit.

The abnormally high chrysotile content of this deposit is probably a result of the intensive shearing that it underwent during or after emplacement. If the friable, chrysotile-rich ore was produced during this pulverization episode, (1) lizardite and/or antigorite in the serpentinite must have been transformed into chrysotile and (2) brucite must have been removed. It is likely that early-formed lizardite/antigorite dissolved in the ground waters which pervaded the highly sheared body and that chrysotile later precipitated from these waters, coating all available surfaces.

### INTRODUCTION

Although the New Idria serpentinite has been known since 1853, there is little difficulty in realizing why it went unrecognized for more than 100 yr as one of the world's largest deposits of chrysotile asbestos. Despite its enormous size and high-grade nature, the physical appearance of the ore is markedly unlike that of almost any other asbestos ore in the world. Most asbestos ores consist of chrysotile in the form of cross- or slip-fiber veins within massive serpentinite rock. Such veining is almost absent from the New Idria body and the ore consists of friable masses of matted chrysotile surrounding fragments of serpentinite rock. The ore is highly sheared and pulverized allowing mining to be carried out by simple, open-pit methods and the production of high quality asbestos by straightforward wet or dry separation processes.

The New Idria serpentinite outcrops over a 50 mile<sup>2</sup> area in Fresno and San Benito Counties, 35

airline miles northwest of Coalinga, California. Early reports described the serpentine material as "mountain leather" or "antigorite... the platy, noncommercial form of serpentine". A minor amount of cross-fiber ore was produced from thin veins and seam fillings near the northwestern edge of the body (Lazure, 1926), but this ore played out in just a few years. The California Division of Mines (Anonymous, 1957) made brief mention of "chrysotile" in the central part of the massif but no evidence was given for this identification. In the late 1950's, J. H. Bright, a Union Carbide Corporation geologist, examined the area and noted that although cross-fiber veins were not to be found, the entire southeastern third of the serpentinite consists of leathery sheets and pellets of friable, asbestos-like material. He reported that the friable ore is not merely a surface weathering phenomenon, but that it extends several tens of feet deep and is relatively uniform over a 15 square-mile area.

Subsequent X-ray diffraction and electron microscope examination indicated that the major constituent of the ore is indeed, chrysotile, the fibrous member of the serpentine group. This identification led to considerable speculation on commercial uses for this unusual form of asbestos, and by late 1959, the town of Coalinga had become the center of asbestos exploration activities of several industrial organizations, and the deposit become known as the Coalinga asbestos deposit. (See also Munro and Reim, 1962; Merritt, 1962; Rice, 1963.)

The Coalinga ore contains more than 50 per cent chrysotile, in contrast to the <10 per cent recoverable fiber in typical cross- or slip-fiber ores. The derived asbestos product was found to be comparable with Grade-7 Canadian fiber and thus in the 1960's appeared potentially useful in standard applications of this grade. Mining of the Coalinga ore in recent years by Union Carbide Corporation, Coalinga Asbestos Company (a joint venture between Johns Manville Corporation and Kern County Land Company) and Atlas Minerals Corporation has caused the asbestos production of the United States to triple since 1960. These companies currently produce nearly 75,000 tons of powdered asbestos each year by both dry and wet processing techniques. In addition to conventional uses for Grade-7 asbestos, *wet-processed* fiber has found many new applications in the paper and plastic industries, in water purification, and in several other specialized businesses (Woolery, 1966).

In support of mining, milling and product development activities of Union Carbide Corporation, a detailed mineralogical study was carried out on the Coalinga ore. The results of this study have suggested a formation mechanism which may be applicable to chrysotile-rich zones and deposits in other serpentinites of the world.

#### EXPERIMENTAL

##### *Sample collection and preparation*

More than 500 samples were collected from summer 1962–1964 from the surface weathering zone, the resistant serpentinite knobs and outcrops, and the pits and stockpiles of the companies then active on the deposit. Nearly 2100 interval samples were also examined from 160 drill holes located on a grid pattern across Union Carbide's property. These samples were collected by W. T. Cohan and M. Genes and represent half of the material recovered from 10 ft intervals of 6 in, rotary drill holes. They were split at the drill site to about 25 lb and further reduced in size to about 5 lb of  $\frac{1}{2}$  in material by alternate grinding, screening and splitting. To obtain finer grained material for analysis, 10–20 g splits were then ground dry in a Waring Blender to about 10 mesh. Additional comminution could be achieved in a Pitchford Selective Uniform Particle Size grinder; however,

\* See Mumpton, F. A. (1974) Characterization of chrysotile asbestos and other members of the serpentine group of minerals. *Siemens Review* **XL1**, 7th Spec. Iss.—X-ray and Electron Microscopy News, 75–84.

samples ground to 325 and 400 mesh were slightly contaminated by the tungsten carbide balls and mill.

Mineralogical examinations were made also on pressed filter cakes which had been prepared by mixing the sample for several minutes in a blender and filtering immediately. Highly purified, gangue-free samples were prepared by dispersion in an aqueous solution of aluminum acetate at about pH 4.5. The dispersed fiber was then decanted from coarser magnetite and platy serpentine, flocculated with sodium carbonate, filtered, and dried. This technique is a modification of procedures reported by Barbaras (1953). By changing settling times and centrifugation conditions, various degrees of purification could be achieved.

##### *Apparatus*

X-ray powder diffraction studies were made with commercial high-angle diffractometers and 114.6 mm dia. powder cameras, using Ni-filtered  $\text{CuK}_\alpha$  radiation. One-inch circles cut from dried filter cakes of asbestos were examined directly by pasting them to glass sample holders. Samples thus prepared have a strong tendency to orient, and basal spacings of the serpentine mineral are greatly enhanced on the X-ray diffraction patterns. Orientation effects can be reduced by spinning the sample in the X-ray beam by means of a rotating specimen holder or by using packed sample holders of 450 mesh powder.

A Powertron 300 W Ultrasonic Cleaner was used to disaggregate and to assist in dispersing serpentine specimens. Electron microscope investigations were made by W. Roettgers with a Siemens Research Model electron microscope, using both water-suspension and preshadowed, carbon-replica preparation techniques. Critical samples were also examined by selected-area electron diffraction. Differential thermal analysis patterns were recorded on an X-Y recorder as a function of e.m.f., using calcined kaolinite as a reference material.

#### CHARACTERIZATION OF SERPENTINE-GROUP MINERALS

The unequivocal identification of members of the serpentine group of minerals is a difficult task which is made even more complex by the presence of more than one polymorph in the same specimen. Most of the samples examined in this study contain at least two of the three principal serpentine polymorphs. A critical review of the problem of the characterization of the serpentine minerals is being prepared for publication elsewhere; however, to support the identifications made in this study, a brief discussion of this problem is warranted.\*

Chrysotile itself is readily distinguished in the electron microscope by its tubular-fibrous habit, but the morphological similarity of lizardite and antigorite precludes their differentiation by this technique alone. X-ray diffraction provides a reliable means of distinguishing the serpentine polymorphs, provided that samples are relatively monomineralic. Mixtures are

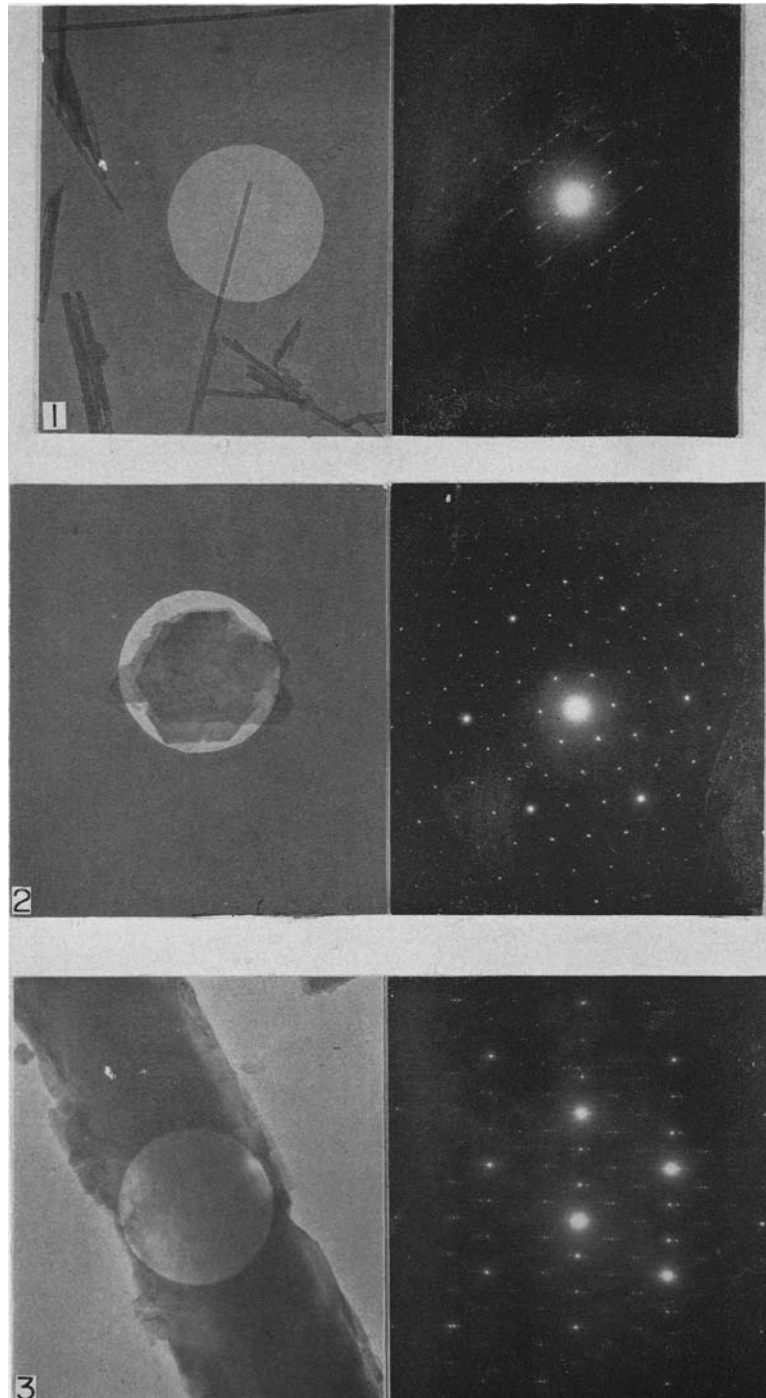


Fig. 1. Electron micrograph and diffraction pattern of chrysotile from the Coalinga asbestos deposit (Green-bladed material). Magnification = 21,000  $\times$ .

Fig. 2. Electron micrograph and diffraction pattern of lizardite from the Coalinga asbestos deposit, in antigorite from Santa Rita Peak (487-52-8): Magnification = 21,000  $\times$ .

Fig. 3. Electron micrograph and diffraction pattern of antigorite from Santa Rita Peak, Coalinga asbestos deposit (487-52-8). Magnification = 21,000  $\times$ .



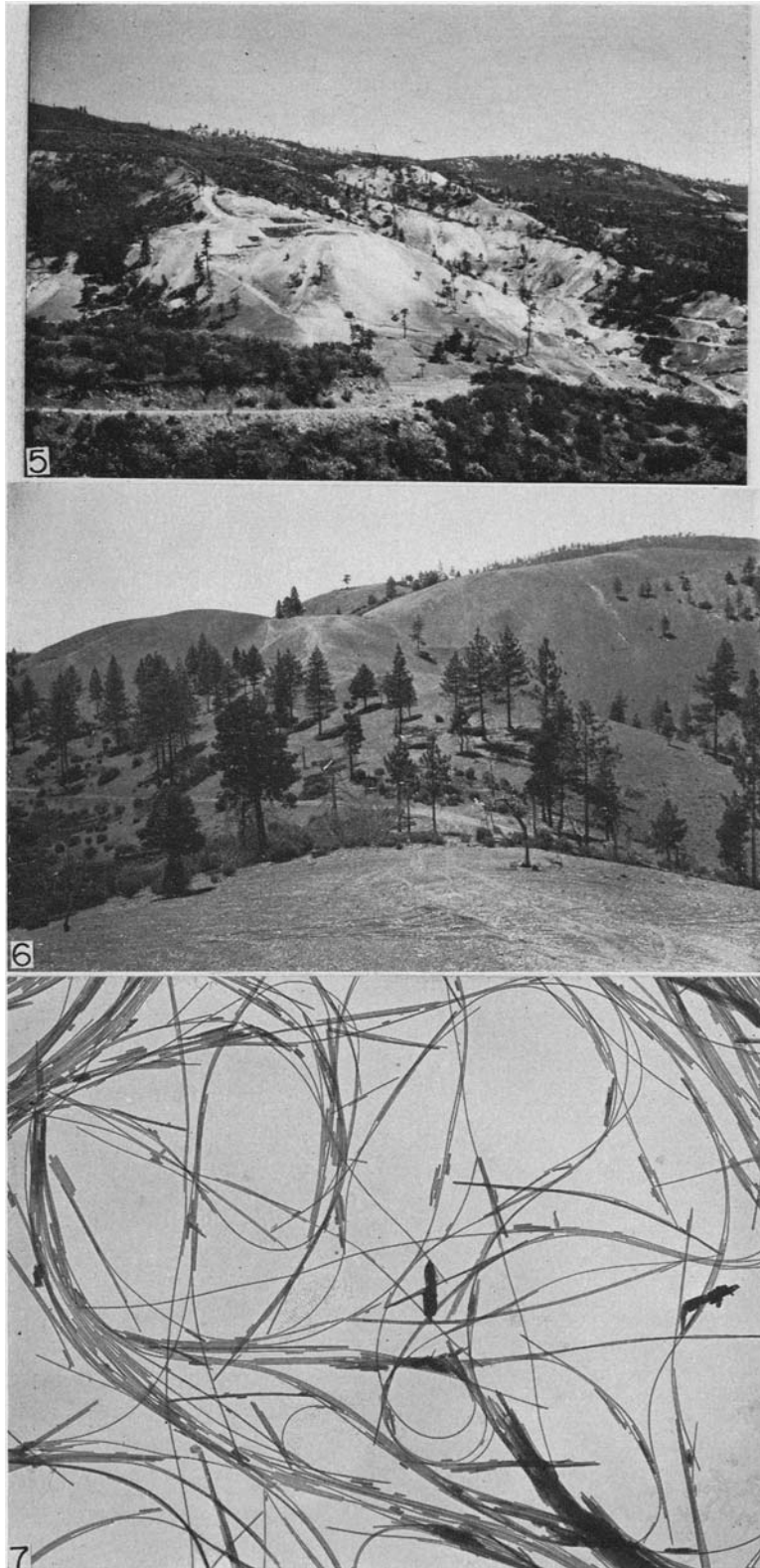
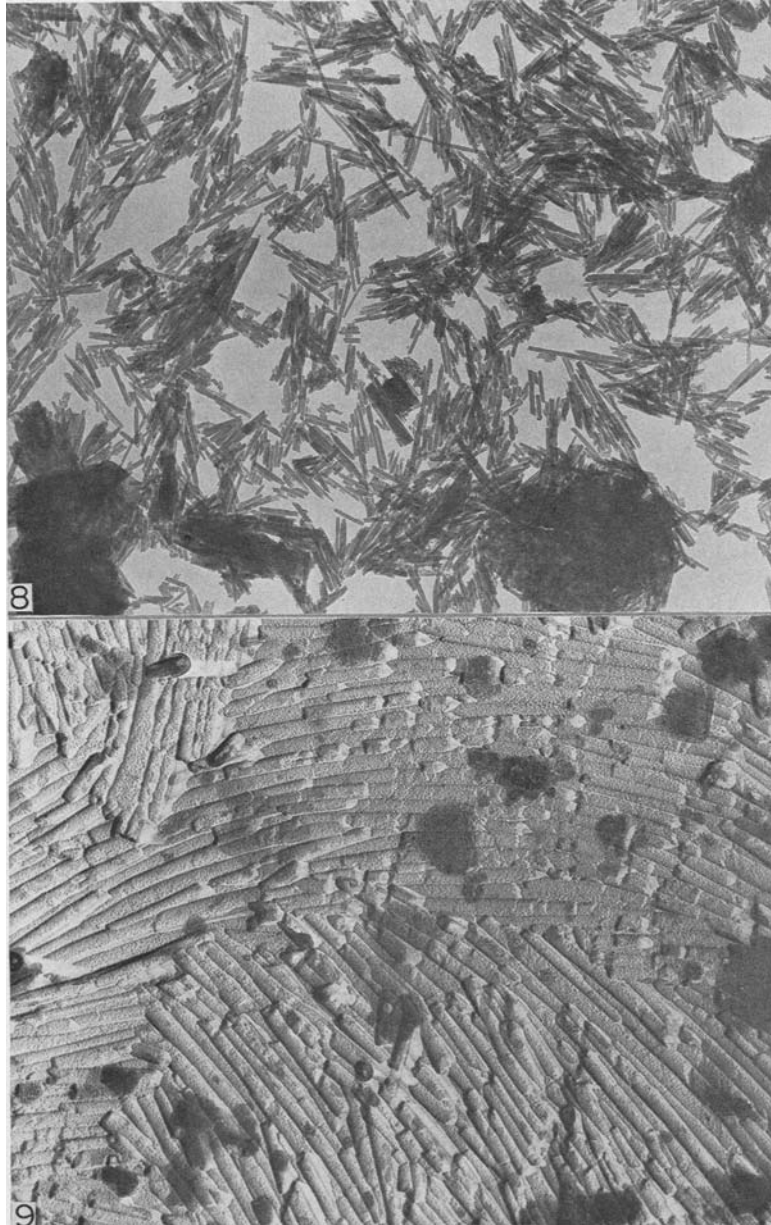


Fig. 5. White, asbestos-strewn slope in the central part of the New Idria serpentinite.  
Fig. 6. Barren slopes covered with green-bladed chrysotile, Coalinga asbestos deposit.  
Fig. 7. Electron micrograph of chrysotile from the Coalinga asbestos deposit. Magnification =  
15,500 ×



**Fig. 8.** Electron micrograph of chrysotile from fragments of massive serpentinite in the Coalinga asbestos deposit (248-43-4). Magnification = 19,500  $\times$ .  
**Fig. 9.** Electron of a replica of chrysotile from green-bladed fragments from the Coalinga asbestos deposit. Magnification = 47,000  $\times$ .





**Fig. 10.** Electron micrograph of a replica of chrysotile from the leathery sheets from the Coalinga asbestos deposit. Magnification = 5000  $\times$ .

**Fig. 11.** Photomicrograph of a thin section of sample 487-44-6, showing serpentine, brucite and magnetite. Crossed nicols. Magnification = 50  $\times$ .

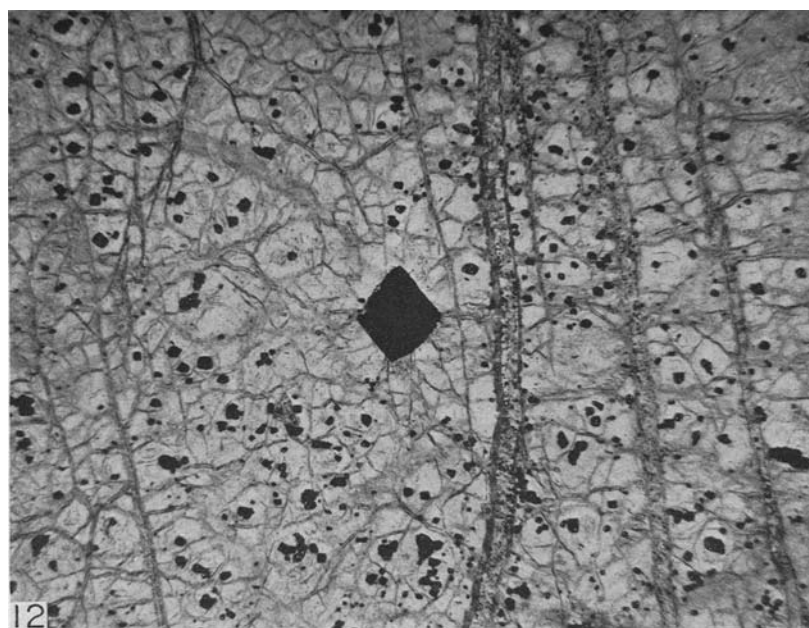
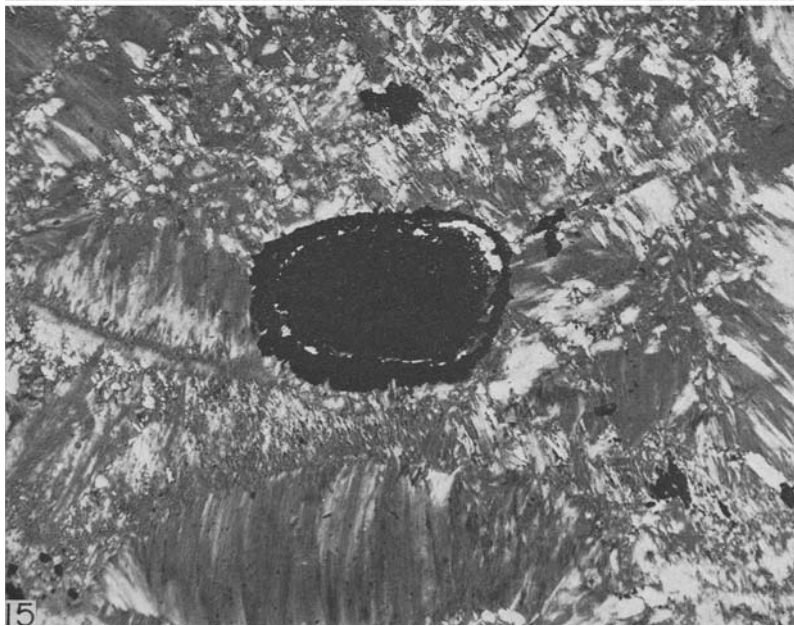
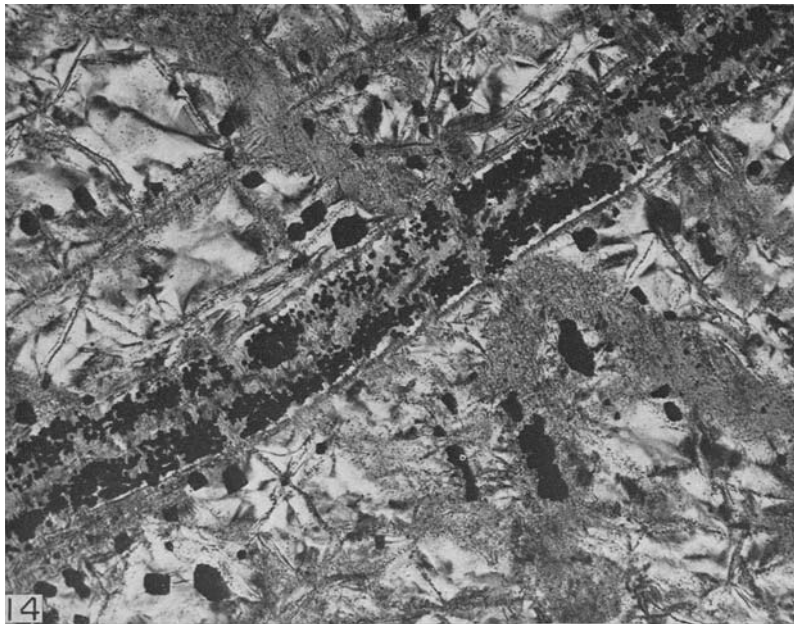


Fig. 12. Photomicrograph of a thin section of sample 487-44-9 showing serpentine (white-gray) with characteristic "mesh" structure and magnetite (black). Polarized light. Magnification = 50  $\times$ .  
Fig. 13. Photomicrograph of a thin section of sample 487-44-6 showing serpentine, brucite and magnetite. Crossed nicols. Magnification = 50  $\times$ .





**Fig. 14.** Photomicrograph of a thin section of sample 487-44-9, showing serpentine and magnetite, and a cross-cutting vein in which magnetite is concentrated near the walls and brucite at the outermost edge and near the center. Crossed nicols. Magnification = 85 ×.

**Fig. 15.** Photomicrograph of a thin section of sample 487-44-6, showing fibrolamellar serpentine surrounding an opaque inclusion. The center of the inclusion is chromite (black) which is surrounded by carbonate (gray-white) which is in turn surrounded by an outer rim of magnetite (black). Crossed nicols. Magnification = 150 ×.



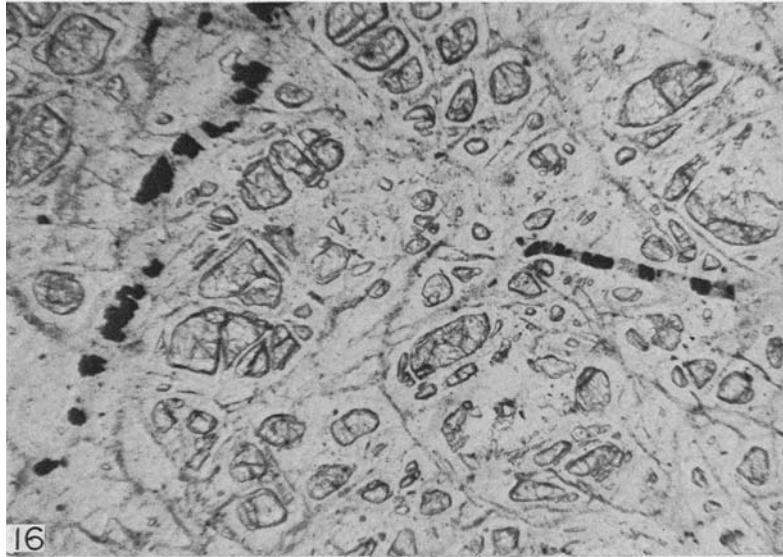
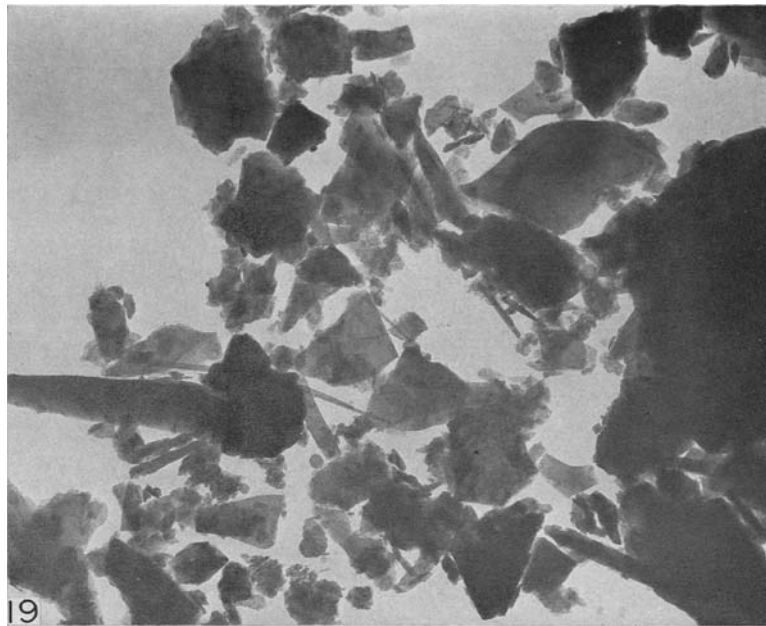
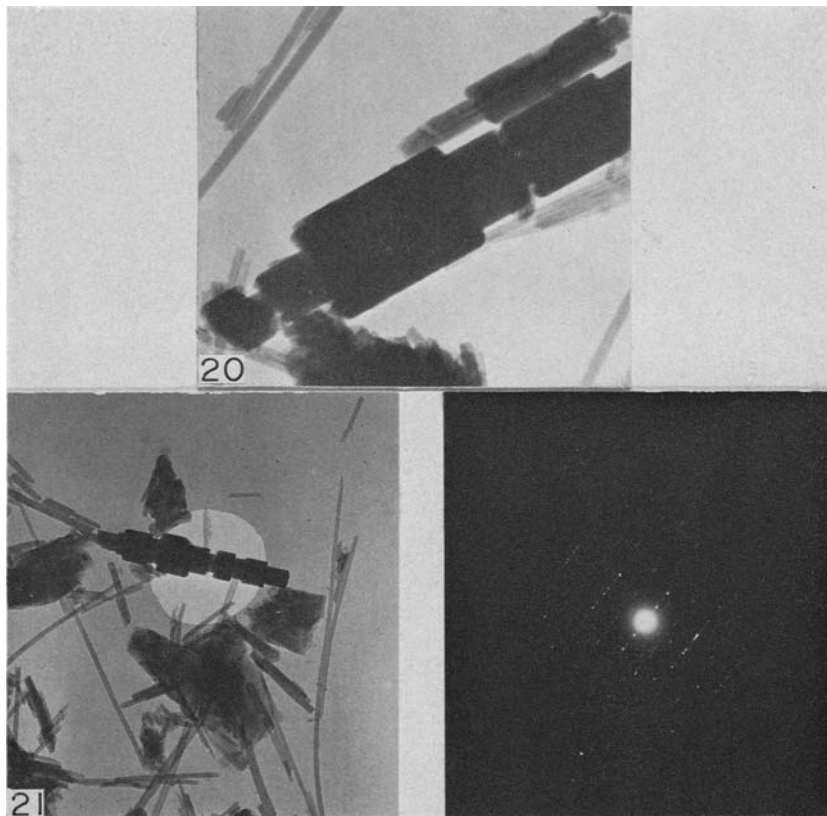


Fig. 16. Photomicrograph of a thin section of sample 487-44-28, showing relict olivine ( $\text{Mg}_{1.82}\text{Fe}_{0.18}\text{SiO}_4$ ) in serpentine. Polarized light. Magnification =  $130\times$ .

Fig. 17. Photomicrograph of a thin section of sample 487-44-28, showing a large relict grain of olivine in serpentine. Polarized light. Magnification =  $130\times$ .



**Fig. 19.** Electron micrograph of antigorite from sample 487-52-8, collected at Santa Rita Peak, Coalinga asbestos deposit. Magnification = 18,000  $\times$ .



**Fig. 20.** Electron micrograph of an unusual form of chrysotile in sample 487-44-6. Note the extremely wide tubes of varying diameter. Magnification = 41,000  $\times$ .

**Fig. 21.** Electron micrograph and diffraction pattern of an unusual form of chrysotile in sample 487-44-6. Note the extremely wide tubes of varying diameters. Magnification = 20,200  $\times$ .



more difficult to decipher by X-ray diffraction because all three polymorphs yield very similar and overlapping patterns.

Although Brindley and Zussman (1959) noted that infrared (i.r.) absorption methods could distinguish antigorite from the other serpentines, results obtained in the present study suggest that the technique is of little use in characterizing mixtures of serpentine-group minerals, due to the close similarities of their i.r. patterns. (See also Luce, 1972.) Faust and Fahey (1962) found that antigorite could be distinguished from the pair chrysotile/lizardite by differential thermal analysis because the former gives rise to an endothermic peak at a considerably higher temperature than does either of the other two. Unfortunately

lizardite and chrysotile yield similar patterns making their distinction impossible by D.T.A. methods. Limited use, however, has been made of D.T.A. data in this study to confirm and support identifications made by other techniques.

To estimate the polymorphic composition of critical serpentine samples an identification scheme was developed using a combination of film X-ray diffraction, electron microscopic and electron diffraction techniques. The relative complexity of the procedure precluded its routine use and only about two dozen specimens were completely characterized in this manner. Based upon the data of Whittaker and Zussman (1956) and upon X-ray patterns of standard chrysotile, lizardite and antigorite, estimates were made of the three principal serpentine polymorphs. The lines which are critical for differentiating the three polymorphs are underlined in Table 1.

Although it is not possible to identify the non-fibrous varieties of serpentine by electron microscopy alone, certain features appear to characterize the polymorphs. Lizardite particles commonly have hexagonal outlines (Fig. 2). Antigorite is generally formless, but thin plates may show characteristic *moiré* patterns (Fig. 3). The most reliable identifications are achieved by selected area electron diffraction, a technique used successfully by Zussman, Brindley and Comer (1957). As seen in Fig. 1 the oriented layer lines of the electron diffraction pattern of chrysotile are distinctive. The pattern can also yield information as the exact polytype of chrysotile present (ortho, clino or para). The electron diffraction pattern of lizardite (Fig. 2) is a relatively simple hexagonal array of spots. Overlapping plates of lizardite may give rise to a multiple arrays, wherein hexagonal patterns are slightly rotated from one another, but the six-fold symmetry is clearly visible. The pattern of antigorite (Fig. 3) is 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).

Table 1. Standard X-ray diffraction data for serpentine-group minerals

Antigorite New Zealand 487-39-5		Lizardite Cornwall 568-22-2		Chrysotile Thetford 568-30-1-1		Lizardite/ chrysotile indices (hkl)
<i>d</i>	I/I <sub>0</sub>	<i>d</i>	I/I <sub>0</sub>	<i>d</i>	I/I <sub>0</sub>	
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	—	—	—	—	—
—	—	<u>3.88</u>	<u>3</u>	—	—	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
<u>2.52</u>	<u>9</u>	—	—	2.54	2	202
—	—	<u>2.49</u>	<u>10</u>	—	—	202
2.44	1	—	—	<u>2.45</u>	4	202
2.38	<1	—	—	—	—	—
—	—	—	—	2.21	<1	204
<u>2.16</u>	<u>4</u>	<u>2.15</u>	<u>6</u>	—	—	—
—	—	—	—	<u>2.09</u>	<u>1</u>	204
1.829	1	1.830	<1	—	—	008
—	—	1.792	2	—	—	—
1.776	1	—	—	—	—	—
1.740	1	—	—	1.743	<1	206
—	—	1.735	1	—	—	—
—	—	1.691	1B	—	—	028
—	—	—	—	1.614	<1	—
<u>1.562</u>	<u>4</u>	—	—	—	—	—
<u>1.536</u>	<u>4</u>	<u>1.531</u>	<u>7</u>	<u>1.535</u>	<u>6</u>	060
1.522	<1	—	—	—	—	—
1.506	<1	<u>1.500</u>	<u>6</u>	—	—	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	402
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	—	—	—	—	—

Underlined *d* values are regarded as diagnostic.

## GEOLOGY OF THE DEPOSIT

### Regional geology

The New Idria serpentinite has been described by several authors and has been the scene of past mining operations for chromite, magnesite, mercury and gem benitoite. A simplified geologic map of the serpentinite area, based on the original work of Eckel and Meyers (1946) and the modifications of Coleman (1957) is shown in Fig. 4. The serpentinite is at the southern end of the Diablo Range, midway between the Great Valley of California on the east and the San Andreas fault zone of the west. It is an elongate oval flanked by upturned sedimentary rocks of the Franciscan and Panoche Formations of Cretaceous age. It generally forms 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

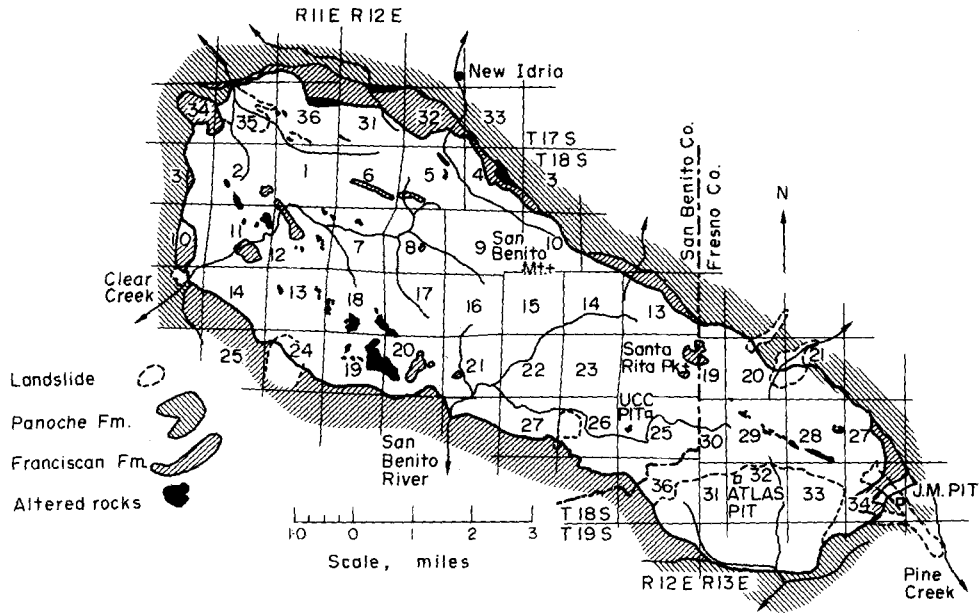


Fig. 4. Simplified geologic map of the New Idria serpentinite. (From Eckel and Meyers, 1946; modified by Coleman, 1957.)

visible, it is generally steeply dipping and marked by high angle faults and/or zones of extensive shearing. Little evidence has been found of contact metamorphism and it is likely that the present position of the serpentinite is the result of tectonic forces, rather than of magmatic intrusion (*op. cit.*, p. 10).

#### Geology of the serpentinite

The New Idria serpentinite is about 4 miles wide and 12 miles long and appears to be a low-temperature alteration product of a pre-existing dunite, although only meagre evidence of the original igneous rock can be found today. Coleman (1957) indicates that the parent olivine-rich assemblage was altered to serpentine far beneath the surface. The resultant serpentinite mass was then injected "cold" into the overlying sedimentary rocks by tectonic forces. Typical mesh-type structures, pseudomorphous after olivine, are commonly observed in thin section, but few grains of relict olivine have been detected. Narrow bands of pyroxene have been encountered in the field, but the overall textural characteristics of the serpentinite suggest that pyroxene was not a major constituent of the original ultramafic rock (*op. cit.*, p. 99). The abundance of brucite, overlooked by Coleman, also suggests that the parent rock was a dunite, rather than a peridotite (*vide infra*).

The great bulk of the New Idria serpentinite has been highly sheared and pulverized and consists of soft, friable sheets and clumps of asbestiform material admixed with a fine serpentine powder. The friable ore has little strength or coherence and crumbles with a touch. Veins of cross-fiber asbestos have been discovered in only three localities, at or near contacts, and may be the result of local hydrothermal phenomena. Hard, dense, competent masses of serpentinite, ranging from fractions of an inch to tens of feet in

diameter, are scattered throughout the body and stand out as resistant knobs and ridges. Many are rounded and take the shape of resistant "boulders" encased in softer, friable material.

A most pronounced feature of the body are myriads of fractures and joints, which crisscross the serpentinite. This phenomenon is most noticeable in the southeastern third of the body, coinciding with the areas of highest grade asbestos. In the northwestern part of the body massive serpentinite is much more common and the quantity of soft, friable asbestos is much less. Figure 5 shows a typical asbestos-strewn slope in one of the high-grade areas of the deposit. In other parts of the body slopes are covered by hard chips of green, bladed serpentine, as shown in Fig. 6.

The total thickness of the serpentinite and of the asbestos ore is not known; however, gravity surveys indicate that the body extends to a depth of 15,000 ft (Byerly, 1954, p. 48). Drill holes in the NW 1/4, Section 25, T18S, R12E collared at an elevation of 4215 ft, and near the New Idria Mercury Mine in Section 32, T17S, R12E and collared at 3780 ft, both penetrated serpentinite at a depth of 500 ft. Lenses and bands of silica-carbonate rocks are abundant in the interior of the serpentinite as well as along the edge of the mass. Many are dike-like bodies which appear to follow prominent fault zones. These have probably formed during localized hydrothermal alteration of the serpentine. According to Bright (1959) these rocks are composed of "chalcedony, quartz, opal and possibly ankerite" and form tough, porous outcrops.

#### 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 are: (1) hard, dense, dark-blue and green fragments of blocky serpentinite, ranging from fractions of an inch to tens of feet in diameter; (2) large, tough, leathery sheets of matted chrysotile, resembling mountain leather, up to several square feet in size; (3) small, brittle, bladed and platy fragments of green serpentinite, up to several square inches in size; and (4) soft, friable greenish-white agglomerates of flaky asbestos, varying from about  $\frac{1}{4}$ -1 in dia., and containing small quantities of both the green-bladed material and the hard, dense, serpentinite rock fragments. Type 4 material makes up the bulk of the ore. Scattered through it are large, massive serpentinite "boulders" (type 1, above), up to several feet in diameter, which have apparently withstood the intense deformation which accompanied or followed the initial serpentinitization process. The grade of the ore is directly related to the quantity of residual serpentinite rock present. Both the leathery sheets (type 2) and green-bladed material (type 3) occur on slickensided surfaces of the "boulders" and apparently coat joint and fracture surfaces.

Chrysotile is the major serpentine constituent of the friable agglomerates and is virtually the only phase present in the leathery sheets and the green-bladed serpentinite fragments. The serpentinite "boulders" are essentially lizardite and antigorite, with lesser 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, chlorite, diopside, and a 14 Å, expandable clay mineral have been identified.

Chemically the Coalinga ore is remarkably homogeneous. Analyses of 10 ft interval composites from a drill hole near Union Carbide's pit in Section 25, T18S, R12E (see Fig. 4) are listed in Table 2. Aside from a surface weathering zone between 0 and 20 feet, few differences in composition are apparent, although the recoverable fiber content of the samples ranges from 35-74 per cent. The magnetite content, as measured by a permeameter technique, is also fairly consistent and varies from about 4-6 per cent.

The magnesia/silica ratios of these samples leave little doubt that brucite is present, a conclusion verified by X-ray diffraction analyses.

#### *Friable asbestos ore*

The soft, friable, greenish-white aggregates generally contain more than 80 per cent short-fiber chrysotile. When dried, this material breaks up readily into a fine powder, containing flakes of matted chrysotile and small particles of hard, gritty serpentinite. Although talc has been reported in the Coalinga ore (Anonymous, 1957; Matthews, 1961; Miller, 1960), these identifications have *not* been confirmed and talc has *not* been found in any of the several thousand samples examined in this study. Strieb (personal communication), however, reports traces of talc in samples from Johns Manville pit near the northeast contact of the serpentinite. These may be due to local hydrothermal solutions and are not typical of the main body.

The fibrous nature of the 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 of the fiber-bundles are close to the values reported by Deer, Howie and Zussman (1962) for cross-fiber chrysotile. X-ray diffraction patterns of several chrysotiles, purified from various types of Coalinga ore, are listed in Table 3 and agree well with those of standard chrysotile as listed by Deer, Howie and Zussman (1962). Although most of the samples appear to be the clinochrysotile variety, no rigorous attempt has been made to differentiate among the several chrysotile polymorphs in this study.

Chemical analyses of chrysotile separated from several different types of ore are listed in Table 4. Although these data yield the approximate composition of Coalinga chrysotile, the actual composition of a particular type of chrysotile in a given sample cannot be pinpointed. The processes used in purifying a sample for analysis tend to fractionate the sample and thus yield products which consist mainly of that material which is easily liberated and separated. The

Table 2. Chemical analyses of drill hole samples Coalinga asbestos deposit\*

	0-10'	10-20'	20-30'	30-40'	50-60'	80-90'	110-120'	160-170'
SiO <sub>2</sub>	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 <sub>2</sub> O <sub>3</sub>	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 <sub>2</sub>	0.43	4.16	1.29	0.82	0.67	0.79	0.70	0.68
H <sub>2</sub> O	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 %†	—	74	53	63	43	52	35	54
Magnetite %‡	—	4.4	4.8	7.5	4.8	4.4	3.3	4.9

\* Located in the SW 1/4, NE 1/4, Section 25 (see Fig. 4).

† Dispersible fiber by Barbaras (1953) technique.

‡ Permeameter measurement.



Table 3. X-ray diffraction data\* for chrysotiles

(hkl)	Chrysotile Zermatt Switzerland† Cross-fiber ASTM 10-381		Chrysotile Thetford Quebec‡ Platy 367-2-1		Chrysotile Thetford Quebec Cross-fiber 568-30-1-1		Chrysotile Cassiar Brit. Col.§ Cross-fiber 367-92-1-5		Chrysotile Coalinga California§ Cross-fiber 487-52-18-1		Chrysotile Coalinga California§ Green-bladed 487-34-3		Chrysotile Coalinga California§ Fiber 367-49-1-1		Chrysotile Stragari Yugoslavias§ Fiber 487-66-1	
	d	I/I <sub>0</sub>	d	I/I <sub>0</sub>	d	I/I <sub>0</sub>	d	I/I <sub>0</sub>	d	I/I <sub>0</sub>	d	I/I <sub>0</sub>	d	I/I <sub>0</sub>	d	I/I <sub>0</sub>
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	—	—	—	—
0010	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

\* Film patterns, Cu K $\alpha$  radiation, 114.6 mm camera.

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

‡ Sample supplied by G. T. Faust, similar to the Coalinga green-bladed material.

§ Samples purified by dispersion techniques.

Table 4. Chemical analyses of purified chrysotile samples from the Coalinga asbestos deposit

	Leathery sheets 367-34-1*	Green-bladed 367-34-2*	Cross-fiber 487-52-18*	Leathery sheets§ No. 4	Mill products§ No. 7
SiO <sub>2</sub>	41.75	41.42	41.02	42.2	41.0
Al <sub>2</sub> O <sub>3</sub>	0.05	0.04	0.31	0.66	0.7
Fe <sub>2</sub> O <sub>3</sub>	1.40	2.05	2.03	1.2	1.3
FeO	0a27	1.61	2.44	0.09	0.95
(Fe)	(1.19)	(2.65)	—	—	—
NiO	0.03	0.07	—	0.04	0.22
MgO	43.04	43.76	40.44	41.4	40.7
CaO	—	0.54	0.25	0.04	0.13
H <sub>2</sub> O	13.46	13.66	13.30	14.25	14.3
Total	100.00†	100.00†	99.79	—	—
Random drill-hole samples					
	585-90-2	585-90-1	487-27-2-6	487-27-3-6	487-27-4-6
SiO <sub>2</sub>	41.92	41.88	40.59	41.16	41.59
Al <sub>2</sub> O <sub>3</sub>	0.36	—	—	—	—
Fe <sub>2</sub> O <sub>3</sub>	0.99	1.09	1.51	1.32	1.17
FeO	0.64	1.08	1.25	0.41	0.75
(Fe)	—	—	—	—	0
NiO	0.09	0.07	0.29	0.26	0.08
MgO	41.76	42.11	41.94	42.18	42.05
CaO	0.07	0.17	0.14	0.22	0.16
H <sub>2</sub> O	13.26	13.60	14.27	14.44	14.20
Total	98.25	100.00†	100.00†	100.00†	100.00†

\* Untreated samples; all others were purified by chemical dispersion techniques and are therefore anomalously enriched in alumina (4–5%). Sample 585-90-2 was chemically dispersed without aluminum compounds, and was washed thoroughly afterwards.

† Recalculated to 100% after correcting for calcite.

‡ Recalculated to 100% after correcting for alumina contamination.

§ From Page and Coleman (1968).

composition of the separated chrysotile may therefore be significantly different from that of the very short-fiber chrysotile, which tenaciously adheres to the gangue materials in the original sample. From these analyses, however, the green-bladed chrysotile appears to contain more than twice as much iron as the leathery-sheet chrysotile. The cross-fiber sample from Coalinga is even more iron-rich and contains significantly more aluminum, likely due to the presence of minute particles of corundum locked between the fibers, as suggested by Faust and Nagy (1967) and Page and Coleman (1968).

Naumann and Drescher (1966) reported that the surface area of Coalinga chrysotile is about  $80\text{ m}^2/\text{g}$ , compared with values of  $20\text{--}30\text{ m}^2/\text{g}$  for chrysotiles from most cross-fiber deposits. They attributed the higher values for the Coalinga material to the absence of "solid matter filling the voids between fibrils".

From electron microscope studies the fiber lengths of chrysotile from the Coalinga deposit vary widely from sample to sample. The longest fibers are several microns in length and are generally found in the leathery sheets and in the flexible platelets of the friable type of ore (see Fig. 7). Chrysotile from the serpentinite rock fraction is considerably shorter and thicker than normal, and length/width ratios as small as 10 or 20 are not uncommon (see Fig. 8). The short, stubby nature of this material may be the result of inhibited growth within compact rock masses, rather than in the relatively "open" environments of fractures and cracks. A replica electron micrograph of green-bladed chrysotile is shown in Fig. 9. The highly oriented nature of the fibers is readily apparent, and contrasts vividly with the swirling mesh of fibers in the leathery sheets, as shown in Fig. 10.

Chrysotile from the green-bladed fragments is also significantly shorter than that from the leathery sheets. Within a single green-bladed lath, the fibers appear to be tightly held in a "whiskbroom" manner with an occasional fiber peeling off an edge. The random, disoriented nature of 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 filled voids and coated surfaces during shear-deformation of the serpentinite body.

In addition to chrysotile, small quantities of platy serpentines (antigorite and lizardite), brucite, and magnetite are also present in the friable portion of the fresh asbestos ore; however, these phases occur primarily in the tiny fragments of hard serpentinite rock which are caught up in the soft, flaky material. Of special importance, however, is the manner in which small flakes of leathery chrysotile completely enclose, in a sandwich fashion, 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 and laths found elsewhere. The soft flakes also enclose particles of white calcite, the age of which relative to the asbestos is not precisely known. Large

flakes and pellets of what appears to be secondary brucite have also been noted associated with the soft, chrysotile agglomerates. Magnetite also is scattered throughout the sheets and embedded in flakes of chrysotile, and many asbestos aggregates can be picked up easily with a hand magnet.

#### *Serpentinite rock fragments*

The serpentinite rock fragments contain most of the gangue materials in the ore and must be separated during milling in order to produce clean, grit-free asbestos products. Nine hand specimens collected from different parts of the deposit, have been studied in detail by petrographic, X-ray diffraction, electron microscope, electron diffraction and thermal techniques.

Petrographically, these samples are similar to most other serpentinites. They consist of dense aggregates of serpentine-group minerals arranged in a breccia-like manner as illustrated in Fig. 11. Randomly oriented aggregates of serpentine with shadowy extinction and fibro-lamellar structure vary in size from 0.05 to 1.00 mm and commonly form "mesh" structures, pseudomorphous after olivine (see Fig. 12). The serpentine has mean indices of refraction of 1.52 and 1.56. The laths or "fibers" of serpentine are length slow, with maximum birefringence of first order yellow. Veinlets up to 0.1 mm wide having parallel orientation and extinction cut across massive serpentine and may be monomineralic chrysotile. This material is *not* cross-fiber chrysotile in the usual sense of the term.

Brucite is abundant in most specimens examined and forms scaly aggregates from 0.1 to several millimeters in size. Intergrowths of brucite and serpentine are common with thin lamella of each mineral alternating with the other, as shown in Fig. 13. Brucite is colorless in thin section and has a characteristic pinkish-yellow interference color. It has a mean index of refraction between 1.57 and 1.58; it is optically positive and interference figures occasionally show anomalous colors. Brucite may be found in magnetite veinlets which are undoubtedly younger than the bulk of the serpentinite specimen (Figs. 11, 13) and which were probably formed during post-serpentinization deformation. Subhedral grains of magnetite occur in all specimens and are commonly associated with calcite and veinlets of brucite. Figure 14 shows such an association, with the outermost edge and center of the vein consisting of brucite and chrysotile(?), and with 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 of magnetite shown in Figs. 12 and 14 may represent two stages of crystallization. Some serpentinite fragments contain as much as 15 or 20 per cent magnetite, although they average between 4 and 6 per cent.

Calcite is commonly found in veinlets with magnetite and brucite. It is usually fine grained, about 0.05 mm in size, and may represent calcium originally present in olivine or pyroxene, and/or may have

Table 5. Mineralogical descriptions and identifications of serpentinite specimens from the Coalinga asbestos deposit

Sample No.	Location and description	X-ray diffraction identification*	Electron microscope and diffraction identification	Differential thermal analysis identification†
487-44-6	Hard, dense, dark green serpentinite from floor of pit in NW 1/4 of Section 25, T18S, R12E	Antigorite Brucite Some magnetite	Chrysotile Antigorite	Chrysotile/lizardite Antigorite Brucite
487-44-9	Unweathered inner portion of large serpentinite "boulder" in pit located in Section 29, T18S, R13E	Chrysotile Lizardite Some brucite Some magnetite	Lizardite Brucite	Chrysotile/lizardite Brucite
487-52-7	Hard, dense, dark blue serpentinite "boulder" from center of pit in NW 1/4 of Section 32, T18S, R13E	Chrysotile Brucite Some magnetite	Chrysotile Some lizardite Some antigorite	Chrysotile/lizardite Brucite
487-52-7-1	Blue-black vein cutting Sample 487-52-7	Antigorite Some magnetite Some uvarovite	Antigorite Trace chrysotile	
487-52-1	Serpentinite "boulder" from same locality as Sample 487-52-7	Chrysotile Antigorite Brucite Some magnetite Trace lizardite	Chrysotile Lizardite Trace antigorite	Chrysotile/lizardite Brucite
487-44-13	Large, reddish colored "boulder" of serpentinite, near pit in NW 1/4 of Section 25, T18S, R12E	Antigorite Trace chrysotile Some lizardite Trace magnetite	Antigorite Some chrysotile Some lizardite	Antigorite
487-44-14	Large serpentinite mass near pit in NW 1/4 of Section 25, T18S, R12E	Antigorite Some magnetite	Antigorite Chrysotile	Chrysotile/lizardite Antigorite
487-44-19	Green serpentinite "boulder" near contact, Section 36, T18S, R12E	Antigorite Brucite Uvarovite	Antigorite Some Lizardite Some chrysotile	Chrysotile/lizardite Antigorite Brucite
487-52-8	Main serpentinite mass at Santa Rita Peak, Section 24, T18S, R12E	Antigorite Some magnetite Trace garnet	Antigorite	Antigorite Trace chrysotile/lizardite

\* Film methods used; *d* spacings listed in Table 6.

† See Fig. 19.

Table 6. 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	
<i>d</i>	<i>I</i> / <i>I</i> <sub>0</sub>	<i>d</i>	<i>I</i> / <i>I</i> <sub>0</sub>	<i>d</i>	<i>I</i> / <i>I</i> <sub>0</sub>	<i>d</i>	<i>I</i> / <i>I</i> <sub>0</sub>	<i>d</i>	<i>I</i> / <i>I</i> <sub>0</sub>	<i>d</i>	<i>I</i> / <i>I</i> <sub>0</sub>	<i>d</i>	<i>I</i> / <i>I</i> <sub>0</sub>	<i>d</i>	<i>I</i> / <i>I</i> <sub>0</sub>	<i>d</i>	<i>I</i> / <i>I</i> <sub>0</sub>
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	1	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	—	—	—	—	1.578	<1	—	—	1.575	<1	—	—	1.577	2	—	—
1.556	4	1.555	4	1.558	2	1.558	2	1.554	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	—	—	—	—	—	—	—	—



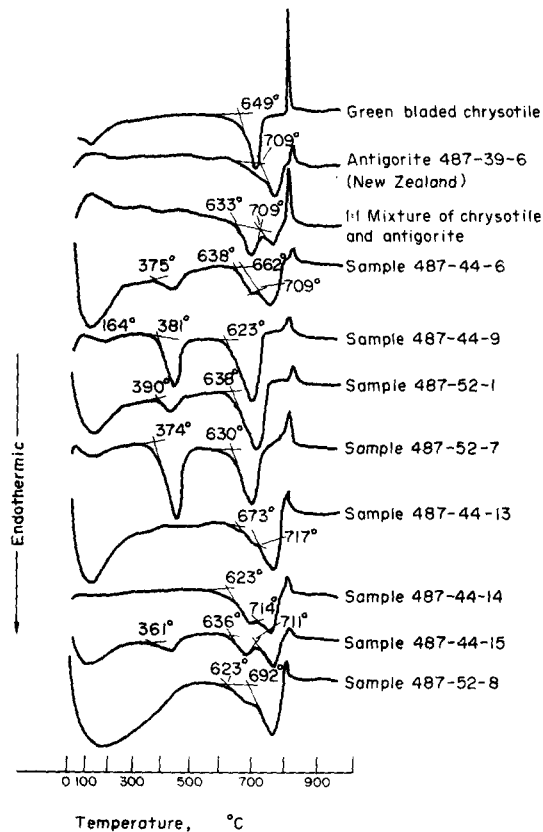


Fig. 18. Differential thermal analysis patterns of serpentinite samples from the Coalinga asbestos deposit.

formed from calcareous ground waters which permeate the mass. Chromite is usually present and is commonly rimmed by either calcite or magnetite. It is much less abundant than magnetite and forms sub-hedral grains about 0.5–2.0 mm in size. It is characterized by a translucent, dark brown color at the edges of otherwise opaque grains. A chromite grain rimmed by magnetite is shown in Fig. 15. Uvarovite garnet has been noted in many samples, usually associated with chromite or in veins cutting the serpentinite. Hostetler *et al.* (1966) reported trace amounts of awaruite ( $\text{FeNi}_3$ ) and heazlewoodite ( $\text{Ni}_3\text{S}_2$ ) in one sample from this deposit by electron probe examination.

Only two specimens examined in this study were found to contain relict olivine in 0.05–0.10 mm size

grains displaying the typical high relief and interference colors of forsterite (see Figs. 16, 17). In thin section olivine grains are in optical continuity and are undoubtedly relicts of larger, pre-existing olivine grains which were originally between 0.25 and 1.50 mm in size. The euhedral nature of the original crystals is apparent in Fig. 17. The optical properties of the olivine, as determined by H. W. Jaffe, are listed below:

<i>Indices of Refraction</i>	<i>Mole Per Cent <math>\text{Fe}_2\text{SiO}_4^*</math></i>
$\alpha = 1.652$ all $\pm 0.0005$	
$\beta = 1.688$	8.5
$\gamma = 1.685$	7.5
Biaxial (+) $2V = 88^\circ$ (Calculated from indices of refraction)	

\* Estimated from indices of refraction.

Using the optical curves of Poldevaart, as presented by Wahlstrom (1955) an empirical formula of  $(\text{Mg}_{1.82}\text{Fe}_{0.18})$  can be derived in which the olivine has an iron content of 8.8 weight per cent FeO. This composition is close to that of the dunitic olivines described by Hostetler *et al.* (1966) in their study of the formation of brucite during pervasive serpentinization of Alpine ultramafics.

Mineralogical identifications of nine serpentinite hand specimens from the Coalinga deposit are listed in Table 5. X-ray data for the samples are listed in Table 6. Although the results of X-ray diffraction and electron microscopy are in good agreement for most samples, the failure to recognize other polymorphs in certain of the samples re-emphasizes the insufficiency of any one technique alone for unequivocal identification of serpentine-group minerals. Differential thermal analysis patterns are shown in Fig. 18, and generally confirm the presence of the major constituents of each sample.

Chemical analyses of many of these specimens are listed in Table 7. The main differences are the wide variations in magnesia/silica ratios which correspond to the presence or absence of brucite in the samples. These data also illustrate the low degree of confidence which should be placed on discussions of serpentinite genesis which are based on chemical analyses of only one or two selected specimens from a large serpentinite body.

Table 7. Chemical analyses of serpentinite 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
$\text{SiO}_2$	36.37	30.93	40.26	35.69	40.67	36.45	26.68
$\text{MgO}$	41.28	43.35	38.16	36.74	38.87	40.67	45.85
$\text{FeO}$	2.60	2.51	2.57	2.77	2.35	2.14	6.28
$\text{Fe}_2\text{O}_3$	3.46	5.53	5.08	6.26	4.10	5.78	3.00
$\text{CaO}$	0.64	0.15	0.17	3.26	0.23	0.48	0.37
$\text{CO}_2$	0.68	0.77	0.18	0.18	0.07	0.60	0.29
$\text{H}_2\text{O}$	12.87	16.96	10.22	11.97	11.02	13.15	17.86
$\text{Al}_2\text{O}_3$	0.21	—	1.45	0.34	0.55	0.24	0.26
$\text{Cr}_2\text{O}_3$	0.38	—	0.32	1.71	0.38	—	—
Total	98.49	100.20	98.41	98.92	98.24	99.51	100.29

\* See Table 5 for locations and descriptions.

Sample 487-52-8 was collected from an acre-size serpentinite block at the top of Santa Rita Peak (see Fig. 4) and consists primarily of antigorite, with a small amount of magnetite and andradite garnet. Chrysotile, lizardite and brucite are virtually absent from this body which apparently has withstood the effects of weathering and stands topographically well above the rest of the deposit. Chemical analyses of two splits of antigorite purified by heavy liquid and magnetic techniques are listed in Table 8. The purified product contains less than 0.5 per cent garnet, by visual estimate, and less than 0.1% magnetite, by permeameter measurements. An electron micrograph of this material is shown in Fig. 19. Relating these data to the composition diagrams of Page (1968) this sample falls at the edge of the antigorite field. It is relatively rich in silicon in the tetrahedral position and contains more octahedral cations than do most antigorites.

An unusual form of chrysotile was noted in sample 487-44-6 by electron microscope techniques and is shown in Figs. 20 and 21. 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, orthochrysotile. The thickness of the cylinders, from 700 to 3000 Å, is much larger than any values reported previously from chrysotile, although similar materials have been observed in synthetic preparations. The origin of the large-diameter chrysotile in the natural sample is unknown.

#### *Brucite in the fresh asbestos ore*

Brucite plays an important role in the New Idria serpentinite, from the original emplacement of the body to its final decomposition in the surface weathering zone, and has been discussed in detail by Mumpton and Thompson (1966) and Hostetler *et al.* (1966). It occurs in almost every type of material from the deposit, averaging 7–8 per cent in typical

ore, and is most abundant in serpentinite fragments where it makes up between 10 and 25 per cent of the rock. It is intimately associated with serpentine, the coexistence of the two phases suggesting strongly that the original ultramafic rock was composed primarily of olivine with very little pyroxene. Mumpton and Thompson (1966) found that the brucite contains about 15 wt per cent iron and has an approximate formula of  $(\text{Mg}_{10}\text{Fe}_2)(\text{OH})_{24}$ . The iron content of the brucite is a critical factor in the susceptibility of the ore to weathering, and exposure of brucite-rich ore to surface oxidation conditions invariably leads to marked discoloration. Many large outcrops of massive serpentinite (e.g. Santa Rita Peak, the reddish outcrop south of the asbestos pit in Section 25, listed as samples 487-52-8 and 487-44-13, respectively, in Table 4) are devoid of brucite suggesting that their "longevity" is due to the absence of this phase, which upon weathering would have led to a rapid disintegration.

#### 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 weathering zone extends to a depth of 20–30 ft and is present over the entire deposit. Blocks and fragments of residual serpentinite have been transformed into soft, brown, crumbly masses, while the surrounding friable asbestos ore has discolored only slightly. Surface coatings of artinite and hydromagnesite are common, the latter mineral also occurring as white, pea-size concentrations immediately above the water table. Weathered serpentinite "boulders" are enriched in pyroaurite and coalingite  $[\text{Mg}_{10}\text{Fe}_2\text{CO}_3(\text{OH})_{24} \cdot 2\text{H}_2\text{O}]$ , a new mineral discovered in the course of this investigation (Mumpton *et al.*, 1965). Amorphous iron oxide is also abundant in highly weathered material, while brucite is virtually absent in the surface weathering zone.

Field observations and laboratory experiments have shown that in the weathering zone iron-rich brucite either dissolves, leaving behind a brown, amorphous residue or iron oxide, or transforms *in situ* into pyroaurite and/or coalingite by oxidation and carbonation. Further weathering destroys these phases, leaving behind more iron oxide. Dissolved magnesium later precipitates as hydromagnesite throughout the deposit.

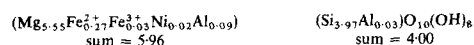
Weathered material has also been found at depths well below the normal weathering zone; some drill holes have intercepted brown-colored, oxidized material as much as 200 ft beneath the surface. It is thought that such materials oxidized as a result of surface conditions being brought beneath the surface along faults or large fracture zones, etc.

Fresh, massive serpentinite "boulders" were uncovered at depths of 50–60 ft in Union Carbide's

Table 8. Chemical analysis of antigorite from Santa Rita Peak

	Split A	Split B
SiO <sub>2</sub>	42.20	41.95
Al <sub>2</sub> O <sub>3</sub>	1.07	1.05
Fe <sub>2</sub> O <sub>3</sub>	0.40	0.46
FeO	3.34	3.33
MgO	39.48	39.44
NiO	0.22	0.31
CaO	0.33	0.36
H <sub>2</sub> O @ 1000°C	12.68	12.39
Total	99.30	99.31

Calculated formula by technique of Faust and Fahey (1962) from average composition:



#### Spectroscopic Data

Co	0.02–0.2
Cr	0.1–1.0 <sup>1</sup>
Cu	0.008–0.08
Mn	0.08–0.8
Pb	0.003–0.03
Ti	0.004–0.04
V	0.002–0.02

asbestos pit in Section 25 and found a few weeks later to be coated with a thin layer of coalingite and/or pyroaurite and brucite. It is likely that the original iron-rich brucite in the ore dissolved in ground water and subsequently precipitated along fractures and joints, thus coating the serpentinite "boulders" at depth. When the "boulders" were exposed to the atmosphere, the redeposited iron-rich brucite oxidized and transformed into secondary pyroaurite and coalingite, probably within a few days or weeks of being exposed. Such a transformation of iron-rich brucite to coalingite was observed to have taken place in the laboratory within a few months (see Mumpton, Jaffe and Thompson, 1965). Coalingite and pyroaurite have also been found as surface coatings or as fracture fillings in a small, highly sheared serpentinite at the southern end of Golden Gate Bridge, San Francisco, California; on ultramafic rocks from the Thetford District, Quebec; and on surfaces in a large serpentinitized ultramafic near Raduša, Yugoslavia. Here also it is thought that iron-rich brucite reprecipitated from ground waters onto fracture surfaces and subsequently oxidized to coalingite or pyroaurite, rather than that the secondary phases were deposited directly from ground water solutions.

Artinite has been found in the surface weathering zone as white encrustations of acicular crystals and as minute tufts of radiating needles on fracture and joints in the serpentinite. It is particularly abundant in the Condor Pit area of Section 29. X-ray  $d$  values are essentially the same as reported by de Wolff (1952).

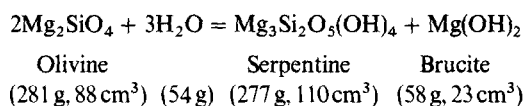
Optical determinations by H. W. Jaffe are listed below:

Biaxial (-)	$\alpha$	= 1.488 (all values $\pm 0.001$ )
	$\beta$	= 1.535 = $y = b$ = elongation
	$\gamma$	= 1.557
	$2V$	= $67^\circ$ (Calculated $\gamma - \alpha = 0.069$ )

#### GENESIS

Classically, Alpine-type serpentinites are thought to have formed by low temperature hydration of pre-existing dunites or olivine-rich peridotites. According to Bowen and Tuttle (1949) olivine reacts with water below  $400^\circ\text{C}$  to yield serpentine + brucite. Turner and Verhoogen (1960, p. 318) assumed, however, from petrographic evidence, that serpentinitization 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. Hostetler *et al.* (1966) found that brucite is a major constituent of many serpentinite bodies of the Circum-Pacific orogenic belt and stated that volume increases up to 40 per cent are conceivable during the serpentinitization process. The general lack of field evidence supporting the migration concept prompted them to conclude that pervasive serpentinitization "... probably results from incremental addition of water derived from country rocks during the tectonic ascent of the ultramafic mass through the earth's crust."

Thus, "isochemical" serpentinitization is accompanied by a considerable increase in volume as follows:



These authors also argued 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 increase attending serpentinitization processes actually assists in the diapiric ascent of the bodies. The process may still be taking place today, accounting for the general occurrences of such bodies in topographic highs.

It is likely that the original serpentinite at New Idria formed in a manner similar to that described above. The mineralogical composition of the serpentinite fragments suggests that the parent ultramafic body was almost entirely olivine. The "serpentine" contains less iron, and the brucite, more iron, than the parent olivine, a relationship brought out also by Hostetler *et al.* (1966) for such bodies in general. According to Coleman (1957) the New Idria mass was probably altered to serpentine far beneath the surface and injected "cold" into the overlying Franciscan rocks. During and after emplacement the body was extensively sheared and 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 in a mix-muller. The end product today is a highly friable, soft asbestos ore, containing variable amounts of uncrushed, residual serpentinite rock.

Several features of the Coalinga asbestos deposit require additional discussion and explanation. Whereas most Alpine-type serpentinite consists mainly of lizardite and/or antigorite with less than 10 per cent chrysotile in the form of slip- or cross-fiber veinlets, the New Idria body contains as much as 80 per cent chrysotile, none of which is in veins, and only minor amounts of the platy serpentine polymorphs. Furthermore, lizardite and/or antigorite appear to be confined to the hard blocks and fragments of massive serpentinite, with the soft, friable part of the ore consisting almost entirely of chrysotile. Brucite is also much more abundant in the serpentinite rock portion of the ore (7-8 per cent) than elsewhere. Thus, if the soft, friable asbestos agglomerates are a "pulverization" product of the original serpentinite, (1) brucite must have been removed during this process, and (2) lizardite and/or antigorite must have been transformed into chrysotile.

The pervasive shearing which this body has experienced no doubt permitted ground waters to move freely through the rock. Much of the brucite produced during the initial serpentinitization probably dissolved in these waters and precipitated later as either hydromagnesite in the surface weathering zone, or as massive deposits of magnesite such as that found in the



northwest corner of the serpentinite. The absence of brucite in areas of intense shearing in other serpentinite bodies has also been noted by Hostetler *et al.* (1966). The transformation of lizardite/antigorite to chrysotile is still not explained, nor has it been carried out experimentally. Page (1968) suggested the the compositional fields and stability ranges of the three members of the serpentine minerals may be different from one another, with partial pressure of oxygen playing an important role in which of the three is formed in a given chemical environment. It may well be that Eh conditions during the initial serpentinization favored the formation of a platy serpentinite, while those prevailing later give rise to the crystallization of chrysotile.

From studies of spring waters issuing from serpentinites and ultramafic bodies of California, Barnes *et al.* (1967) and Barnes and O'Neil (1969) suggested that chrysotile can precipitate directly from ground water. This hypothesis is noteworthy in the light of samples collected from a shallow ore-pit in Section 34, T18S, R13E near the northeastern edge of the serpentinite. Here soft, spongy masses of leathery chrysotile occur saturated with water and admixed with  $\frac{1}{8}$  in pellets of hydromagnesite. The hydromagnesite is undoubtedly a late-stage precipitate from ground water and there is reason to believe that the chrysotile is also. If chrysotile can crystallize directly from ground water solutions, it is not unlikely that most of the chrysotile of the Coalinga asbestos deposit formed in a similar manner—*by the dissolution of lizardite and antigorite from the original serpentinite and the reprecipitation of chrysotile on all surfaces of the sheared and pulverized mass.*

Although they have not been examined in as much detail as the Coalinga deposit, several other asbestos bodies and shear zones within serpentinite masses exhibit mineralogical features which lend credence to the dissolution–reprecipitation mechanism of asbestos formation discussed above. Although lizardite is the dominant polymorph in the massive serpentinite, the powdery, friable material in zones of intense shearing in a small ultramafic body south of Clear Lake, California, is invariably chrysotile by X-ray diffraction and electron microscopic techniques. Similar chrysotile-rich shear zones have been noted in serpentinites at Red Mountain, California; Gasquet Mountain, California; Rattlesnake Mountain, California; Ardino, Bulgaria; and Kraubath, Austria. Coleman and Leith (1971, p. 316) noted a “. . . general increase of clinochrysotile in highly sheared areas . . .” of the Burro Mountain, California, massif. The chrysotile content of the sheared serpentinite zone surrounding the Belvidere Mountain, Vermont, ultramafic is apparently greater than that of the more massive parts of the body (Cady *et al.*, 1963). An apparent increase in chrysotile content of shear zones surrounding other Vermont serpentinites was noted by Chidester (1962), although it is unfortunate that detailed characterization of the serpentine polymorphs was not undertaken in that study.

The only other asbestos deposit which has a physical appearance similar to that of the Coalinga deposit is the Stragari deposit in southern Serbia, Yugoslavia (Miller, 1952; Grimšičar and Očeppek, 1959). The deposit was examined by Mumpton in the summers of 1967 and 1970. Chrysotile asbestos is being mined at Stragari from a 100–200 m wide shear zone at the contact of a large serpentinite and an enclosing limestone. The ore is almost identical to the Coalinga ore in that blocks and fragments of hard, dense, massive serpentinite are coated and surrounded by large leathery sheets and friable agglomerates of chrysotile. Fiber produced from this deposit is also of the high surface-area variety. Although only a trace of cross-fiber asbestos has been noted in this deposit, the ore contains 50–60 per cent recoverable chrysotile fiber, most of which is also of the subgrade-7 type. The geological location of the ore zone and the physical and mineralogical characteristics of the ore suggest an origin similar to that postulated above for the Coalinga deposit.

A newly discovered “slip-fiber” asbestos deposit near Cuicatlan, Oaxaca, Mexico, was recently examined by Mumpton and found to be not-at-all like a typical slip-fiber ore. Instead, the ore consists of fibrous asbestos coating all available surfaces of a highly sheared and fractured serpentinite. The fracturing and shearing appear to be randomly oriented and individual “veins” can not be traced more than an inch or two. The amount of chrysotile in this ore approaches 25 per cent, although the recoverable fiber (Grades 4, 5 and 6) by conventional dry-lift methods is only about 8–10 per cent. Here also the principal polymorph of the massive serpentinite is antigorite, while that of the fibrous material is chrysotile. It is not unlikely that the asbestos fiber in this ore formed by the dissolution of antigorite from the serpentinite rock and reprecipitation of chrysotile from ground waters which saturated the sheared and pulverized body. It appears that we must begin to consider such a mechanism of formation for all such highly sheared and fractured asbestos deposits, and perhaps for cross-fiber ores also.

It is indeed fool-hardy to offer a hypothesis on the origin of chrysotile asbestos, especially when detailed mineralogical and geological studies have been made on only one unusual type of deposit, and when necessary experimental data are not available. However, the very fact that the Coalinga deposit appeared to be unique, prompted the authors to develop ideas about its origin which were different from those established in the literature for “normal” cross-fiber deposits but which were not inconsistent with the mineralogical, chemical and field data. This mechanism involves (1) formation of serpentinite from an original ultramafic body, (2) intense shearing and pulverization of the serpentinite and concomitant saturation with ground waters from the enclosing sedimentary column, (3) dissolution of lizardite–antigorite and brucite from the hard, dense, massive serpentinite during or after tectonic pulverization and

(4) subsequent precipitation of chrysotile from these solutions on all available surfaces in the sheared mass. The authors suggest that such a mechanism may also be responsible for the abundance of chrysotile in shear zones of numerous serpentinite bodies throughout the world, in the Stragari asbestos ore in Yugoslavia, and perhaps in the intensely sheared serpentine zones of the several other deposits mentioned above.

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