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Coalinga Chrysotile: A Short Fibre, Amphibole Free, Chrysotile: Part V – Lack of Amphibole Asbestos Contamination

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Key Words

Coalinga chrysotile • New Idria • Serpentine • Amphibole • Tremolite • Asbestiform

Abstract

Exposure to asbestos in the indoor built environment has been a concern for many years. The most common exposures in that setting are to short ultra-thin, naturally defibrillated form of fibrous asbestiform chrysotile and possibly trace amounts of short, non-asbestiform amphibole. Coalinga chrysotile is a short fibre mineral that was mined from a large ore body in California. It has been investigated in considerable detail since, although it is widely believed to be amphibole free, evidence for this has not hitherto been summarised. Analytical results from investigations that directly searched for amphiboles and geological studies from which the presence or absence of amphibole can be inferred, have indicated that Coalinga chrysotile is free of amphibole asbestos. Indeed, numerous investigations, performed over almost half a century, using a variety of techniques including the most sensitive methods, and studying many thousands of samples have failed to find any amphibole asbestos in Coalinga chrysotile. Only very rarely have non-asbestiform, "non-friable" amphibole (so-called cleavage fragment) minerals been found in the New Idria serpentine body but away from the ore zone. A large body of animal and human evidence indicates such cleavage fragments lack biological potential.

Introduction

Exposure to asbestos in the indoor built environment has been a concern for many years. The most common exposures in that setting are to short fibre chrysotile and possibly trace amounts of short, non-asbestiform amphibole [1]. Since the study of materials with similar exposure profiles may provide insight into the putative risks associated with exposures in the built environment, Coalinga chrysotile, from the New Idria serpentinite ore body in California (Figure 1), has been investigated since it is almost totally short [Chatfield and Ilgren, in prep.] and widely believed to be amphibole free. However, the amphibole content of Coalinga chrysotile has not hitherto been formally reported in a detailed summary fashion. This review therefore not only compiles the analytical investigations that have directly searched for

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amphiboles in Coalinga chrysotile but also details the evidence that indirectly indicates that this form of chrysotile is free of amphibole asbestos. This is particularly important in the continuing debate about the safety of asbestos since animal studies [2–8] and human observations [7,9–11] strongly suggest Coalinga chrysotile lacks pathogenic potential. It has been assumed, on the basis of human studies [12–17] and other analytical data (e.g. see [18]), that the absence of tremolite amphibole asbestos partly explains why Coalinga chrysotile is not pathogenic. This review demonstrates that numerous investigations, performed over almost half a century, using the most sensitive methods, a wide variety of techniques, and studying many thousands of samples, have failed to find any amphibole asbestos in Coalinga chrysotile. Only very rare, non-asbestiform, "non-friable" amphibole (so-called cleavage fragment) minerals have been found in the New Idria serpentinite body exclusively away from the ore zone. A large body of animal and human evidence indicates such cleavage fragments lack biological potential [19].

Direct Evidence of Purity – Analytical Studies of Coalinga Chrysotile

Bulk Samples of Ore and Soil

At least 11 investigations of ore ([20–29]; also Van Balen, 1992 pers comm) and soil [30] from the New Idria deposit have been conducted. Thousands of samples have been analyzed. Not one has ever found amphibole asbestos. A multitude of techniques have been employed. These include petrographic (optical) microscopy [21], chemical [21], spectrographic [21], differential thermal [23], electron microprobe [22], X-ray diffraction (XRD) [21–27,31,32], fluoro–XRD (Van Balen, 1992 pers comm), petrographic thin section microscopy with electron back scattering [29], and transmission electron microscopy (TEM) – XRD with and without acid leaching [28]. Some studies analysed a few ore samples, e.g. [21–23,27] whilst others studied thousands systematically through the Northern part, e.g. ([25]: >6000 samples) and, more randomly, through the Southern part of the deposit (Mumpton, pers comm). Some studies examined not only current ore deposits, including stockpile feed and tailing piles, but also historical samples from areas of the deposit that had not been mined since the late 1950s, using the most sophisticated analytical techniques [28]. Other studies sampled areas where tremolite asbestos would be expected to occur on petrological grounds, e.g. at the margins of the deposit or along the surface of tectonic inclusions ([29]; also Van Balen, 1992 pers comm). None was found. One study examined silt and sand from streambeds in the New Idria region (see [30] table 4.3, pp. 4–6) and concluded that "all of the asbestos identified was chrysotile".

Five studies reported finding amphiboles in their investigations of the New Idria deposit. However, these were only found in extremely small quantities distant from the ore zone. Coleman [20,33] noted non-asbestiform amphiboles largely associated with benitoite ("California's State Gem") and jadeite. These were found

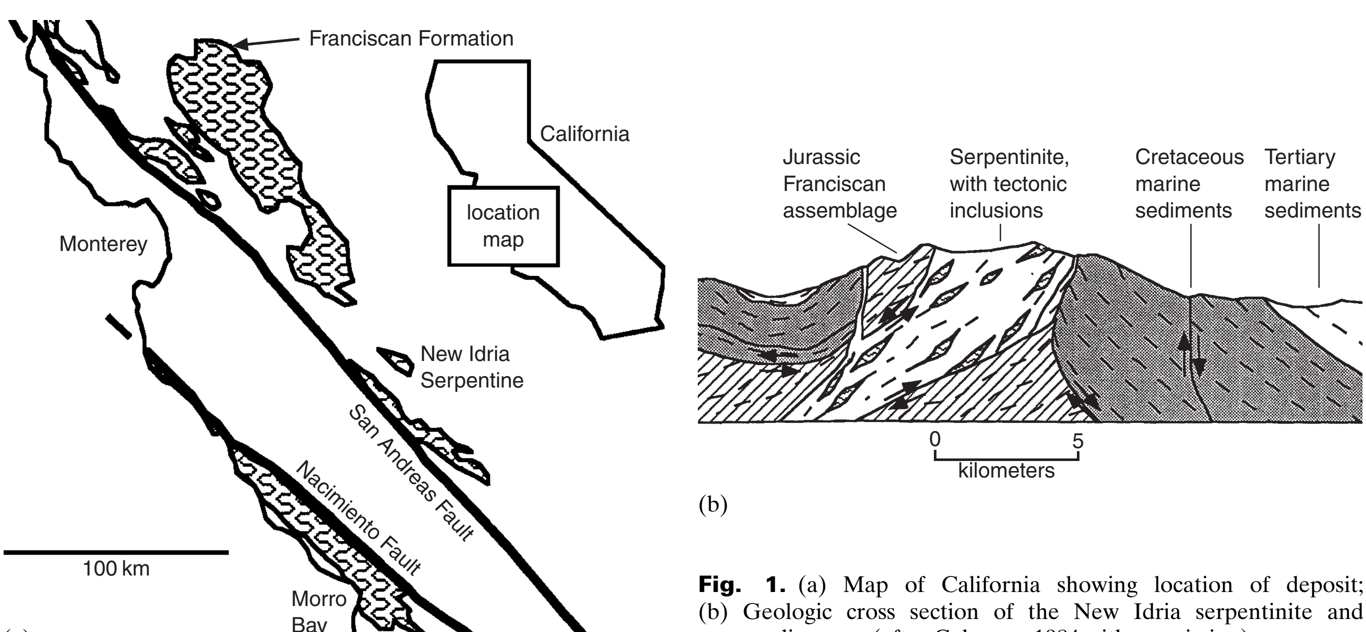


Fig. 1. (a) Map of California showing location of deposit; (b) Geologic cross section of the New Idria serpentinite and surrounding area (after Coleman, 1984 with permission).

outside the asbestos ore zone either in the Gem Mine[1] or as "minute rinds along the surfaces of tectonic inclusions" [33] (Coleman, 2002 pers comm). Bright [24] found barkevite, an exceedingly rare, brittle, non-asbestiform amphibole, in very limited amounts along inclusions in a syenite dyke. Van Balen [29] found very small quantities of various non-asbestiform amphiboles, including a newly identified "blue sodic-calcic" amphibole (one third of the way between winchite and eckermannite), winchite, actinolite, crossite (intergrown with natrolite), glaucophane, kaersutite, and a very rare, titanium-rich amphibole. The Bureau of Land Management Environmental Impact Statement [34] also described these non-asbestiform amphiboles including tremolite and barkevite, associated with rare gemstones or "collectible minerals" from "one of the most highly mineralised areas in California". Cooper et al. [35] said acicular crossite was commonly found in the area of the Victor claim whilst tremolite, though present, was one of the "less important minerals recorded in the area" (also see [29]). The Victor claim is situated more than 6 miles from the ore zone and is also on a totally different drainage area than the mine (Coleman, 2004 pers comm).

Processed Ore and Commercial Product

At least 18 different investigations of commercial product from the New Idria deposit have been conducted. Large numbers of samples have been analysed. Not one has found amphibole. Numerous analytical techniques have been employed. These include petrographic (optical) microscopy [21], chemical analysis [21,28,36,37], spectroscopy [21,36–38], phase light microscopy [27,39,40,41], petrographic microscopy [36,37,42], XRD [21,31,36,37,41–45], TEM [46,47] and TEM coupled with XRD [28,27]. Three studies examined acid-leached samples: one employed XRD alone [31]; another used SEM–XRD [48], and a third used TEM–XRD [28].

Amongst all of the analyses of commercial product conducted to date, only two claimed to find amphibole. In one, anthophyllite was reported in a single sample ([43]; Table 7.7). However, Wicks [31] re-examined all of the XRD data from that study and failed to confirm the presence of amphibole. Wicks [31] concluded that the tracings had been incorrectly interpreted possibly due to "sample preparation problems" ([43] see pg. 143) related to "milling, grinding and freezing" ([43] see p. 111) leading to "poor precision of the peak data" ([43] see p. 112). In the other study, Langer [27] examined one commercial sample, RG100, by analytical electron microscopy interfaced with a dispersive X-ray spectrometer and found an "occasional electron dense mineral fibre morphologically resembling an amphibole with an "aspect ratio greater than 15:1". The selected area electron diffraction pattern, however, was said to suggest "a complex structure not unlike a talcbole from any one of many talc deposits in the United States" but the structure could not be identified conclusively ([27]; also Ross and Lee, 1995 pers comm). Langer [49] subsequently testified that none of his earlier studies had demonstrated Coalinga chrysotile to be contaminated with amphibole asbestos of any kind.

"Positive" control samples known to contain tremolite were included in two studies. One of the two was negative, although this might be accounted for on the basis of detection and/or sampling bias. Thus, Wicks [31] analysed a non-leached sample from the Jeffrey mine in Quebec and a leached sample of UICC/B Canadian chrysotile [50]. Tremolite was not found in either sample. However, tremolite is definitely found in the Jeffrey deposit [18] albeit sporadically, focally and in low levels [18]. This indicates that the UICC/B sample, 60% of which is from the Jeffrey mine, should also certainly contain tremolite. Indeed, the UICC/B sample ([51,52]; also Chatfield, pers comm), and samples from certain individual Quebec mining areas have also been found to contain tremolite. Thus air ([32] from the Bell's mine and ore ([32], see Table 5.6) from the Black Lake, King Beaver, Thetford, Normandy, and Jeffrey mines have been found to contain tremolite and sometimes glaucophane as well (also see [18]). Recent reports by Kohyama et al. [53] and Frank et al. [54] claimed that amphibole was absent from UICC/B. However, neither study examined the UICC/B samples using acid digestion concentration methods. Frank et al. [54] suggest that their work "extended" an earlier "supportive" study of Bowes and Farrow [55]. The latter, however, appeared to have done only a chemical elemental analysis. Wicks' [31] failure to find tremolite in UICC/B could have been due to detection bias and this is supported by the second study to use a positive control sample, namely that of Pooley [28]. Thus, Pooley [28] analysed Bell's 7M chrysotile, a sample shown to contain almost 1% tremolite by others [56]. Pooley [28] was not able to find tremolite in the Bell's sample with XRD alone. With electron microscopy alone, Pooley [28] could locate tremolite fibres with difficulty, but after acid leaching tremolite fibres could be easily identified using TEM and XRD (see [28] Appendix 11 for details). Thus, Wicks' [31] failure to observe tremolite (at levels of detection which he estimated to be *c.*1–2%) may have been due to his failure to employ both TEM and XRD in conjunction with acid leaching in a manner similar to Pooley [28] which would have reduced the detection limit to less than 0.1% [28]. Hatfield [48] also failed to find amphibole in Coalinga chrysotile using an acid digestion technique and SEM. Longo [57] was, curiously, unconvinced of Hatfield's negative result even though Hatfield worked in Longo's laboratory. Longo [57] said he remained unconvinced since he had not seen Hatfield's data, which was particularly odd since Hatfield had already testified under oath to the negative result.

Two processed samples, COF25 and RG144, were used in the chronic Coalinga chrysotile inhalation bioassays. These were conducted with the COF25 [2,3,4,58] and RG144 [8] Coalinga chrysotile samples at the NIEHS and the Fraunhofer Institute, respectively. Neither of these samples was found to contain amphibole. COF25, and two other very similar preparations known as "CIM" and "CIP" were prepared exclusively for experimental study[2] by the Bureau of Mines (BUM) and the Illinois Institute of Technology & Research Inc. (IITRI). These were carefully characterised using XRD between 1974 and 1984 (see [43], fig 5.1, pp. 49, 73, 82–85; patterns 24, 25–30, and 47, Appendix "A"; and Tables 3.1, 7.3, 7.7, 9.2–9.5, 9.16–9.18), ([44], Table 11); ([45], p. 16). COF25 was then re-examined using XRD after acid leaching by Wicks [31], who also reassessed the original CIM and CIP XRD tracings. RG144 (also known as HPO) and a variety of nearly identical products, have also been analysed (RG144: [28,31,41]; RG100: [27]; SG130 [47]; RG244: [28,47]) using analytical methods that include XRD with acid leaching [31] and TEM–XRD with acid leaching [28]. Thousand of fibres have been examined in these studies. Amphibole fibres have not been found in any of the samples.

Amphibole fibres were also not found in Johns Manville (JM) [36–40,42] and Atlas (product AZ20, Addison, 1991 pers comm) commercial products. This again supports both the homogeneity and the purity of the deposit.

Air Sampling Analyses

There are three sources of air sampling data. EMS [59] laboratories analysed air samples using TEM for California EPA Region IX (25 March 1988). Only chrysotile was found. The R J Lee group conducted air monitoring studies at the King City (KCAC) mine [60] and mill [61] under contract to the California Air Resource Board. Out of 21 mine and 21 mill samples, many thousands of fibres were examined and only one amphibole fibre was found. This was less than 5 μm in length [61]. Further details of the type and width of this fibre are no longer available (RJ Lee Group, 20 June 2002 pers comm). Finally, air samples have been taken by inspectors for the Monterey County Air Resources Board (MCARB) at the KCAC mine and mill from 1992–2002 and examined with TEM. Thousands of fibres have been examined. No amphibole fibres have been found (MCARB, 2002 per comm).

Indirect Evidence of Purity

Geological and Mineralogical Forces Contributing to the Absence of Amphibole

The mode of formation of the New Idria deposit is unique [20,24,25, 29,62–66]. These unique features reflect the genesis of the deposit which, in turn, explain why tremolite is not found in Coalinga chrysotile. The explanation generally rests on two facts. First, the physical and chemical conditions are not conducive to its formation. Second, the dynamics of emplacement contribute to the removal of any amphibole that may been present initially.

Dynamics of Emplacement

Physical forces and subsequent chemical sequestration contribute to the absence of tremolite in the New Idria deposit. Thus, physical forces break up the serpentine which facilitates the entrance of carbon dioxide-rich fluids. These, in turn, bind free calcium ions and so limit the appearance of tremolite in the formation of Coalinga chrysotile. The physical forces include pulverisation, extreme shearing and dissolution, all of which are part of the genesis of the New Idria deposit. The New Idria serpentinite[3] originates at great depths from the oceanic mantle as a soft, mushy "plastic plug" [24]. This takes place in a manner similar to "many [other] serpentinites [that] represent displaced parts of oceanic mantles" [67,68]; also see [18,69]. The New Idria serpentinite is said to grow through active "diapirism" [70]. The diapir (an anticlinal fold in which a mobile core has broken through more brittle overlying rocks) resembles a "dome" [69]. The "dome", in this case, is situated over dense swarms of low-magnitude earthquakes that place it under stress from seismic movement along the San Andreas fault. These forcefully inject the serpentine mass upward in the solid state.

The intense tectonic movements of the San Andreas Fault also compress the serpentinite, causing it to rise further [63,70]. Thousands of tectonic events (likened to the physical grinding that takes place with a ball and rod mill) shear and pulverise the ore body. These forces may help "grind" accessory minerals off the fibres and "tectonically mill" or open the fibres themselves [63].

The ascending serpentinite requires water to form and absorbs water from the surrounding sedimentary waters ([69] p. 239; [70]). This causes it to rise to accommodate the attendant volume increase [70]. Coleman has noted (2004 pers comm): "Serpentine requires water to form and takes up to 33% more space than the olivine it replaces and it also is much lighter and so rises upwards in the Earth's crust as a diapir much like a salt dome." As this takes place, the serpentinite undergoes further deformation as blocks within the rising mass rotate and undergo further internal shearing by grinding on themselves ([22], p. 88; [69]). Coleman again states (2004 pers comm): "The tectonic inclusions are incorporated into the serpentine that acts as an elevator because it is light and buoyant."

The sedimentary and meteoric ground waters (or those which circulate as part of the water cycle) at New Idria are relatively rich in carbonates. These fluids gain access to the serpentine after they are broken up by the extreme tectonic milling. Any calcium that exists is bound up as carbonates leaving little or none available for incorporation into silicates such as tremolite. In this way, sequestration can contribute to the removal of accessory minerals potentially contaminating the serpentine (also see [69], pp. 203–205).

Physical and Chemical Factors Required for the Formation of Amphibole within Serpentine Deposits

The conditions under which the New Idria deposit formed are not conductive to the formation of amphibole. The physical and chemical factors required are not present. This explains why "chrysotile and amphibole cannot form in the same rock" [69] and why chrysotile ores, in and of themselves, are naturally amphibole-free [18].

"Amphibole minerals can form from serpentine by two geologic processes, i.e. by heating and chemical alteration. The requirements for this to occur are further defined in solid state syntheses of the amphiboles" [66]. Temperature works in concert with other determinants such as calcium and silica, which were also found to be the principal physico-chemical controls of amphibole growth in the Canadian Jeffrey deposit [18]. Similar controls also operate at New Idria.

Temperature

The temperatures at which serpentisation occur at New Idria are "incompatible with the formation of tremolite"[4] ([29], pp. 3–7, 3–73; also see [65]). They are simply too low. Tremolite is not a stable low temperature product of the hydration of fertile ultramafic rocks but tends to form at temperatures greater than 400°C ([29], figure 4.11]). By contrast, "chrysotile asbestos is the habit of serpentine that forms at low temperatures in rocks that are being deformed" ([29], pp. 7–20; also see pp. 3–7, 3–26, 3–73, 4–64, 4–67; figure 4.12a]) and serpentine minerals are not normally stable above 500°C (Coleman, 2004 pers comm.).

Chemical Determinants

The composition of the basic starting materials found at New Idria are said to differ from those found in many other chrysotile ore bodies (Van Balen, pers comm). Certain components are important determinants of amphibole formation.

Calcium

Calcium is probably the primary determinant of tremolite formation. Calcium, and calcium-bearing minerals such as carbonates and talc, are nearly absent from the New Idria deposit [25,26,29] (Coleman, 2001 pers comm).[5] Since tremolite is a calcic amphibole, "the host rock must contain calcium for it to form" ([69], pp. 99, 214; [66], pp. 49, 51). Indeed, "calcium-rich minerals cannot form in a serpentine-rich rock, except in unusual local occurrences" [31]. This is important since calcium is one of the principal physicochemical controls of amphibole growth not only at New Idria ([69], p. 121), but also in other chrysotile deposits as well [18].

The near absence of calcium is also partly explained by the fact that "[it] is frequently lost to the rock body during serpentisation, so that the bulk composition of the serpentinite is lower in calcium than the precursor ultramafic rocks" [29], pp. 4–64 and 7–15; also see [72].

Silica

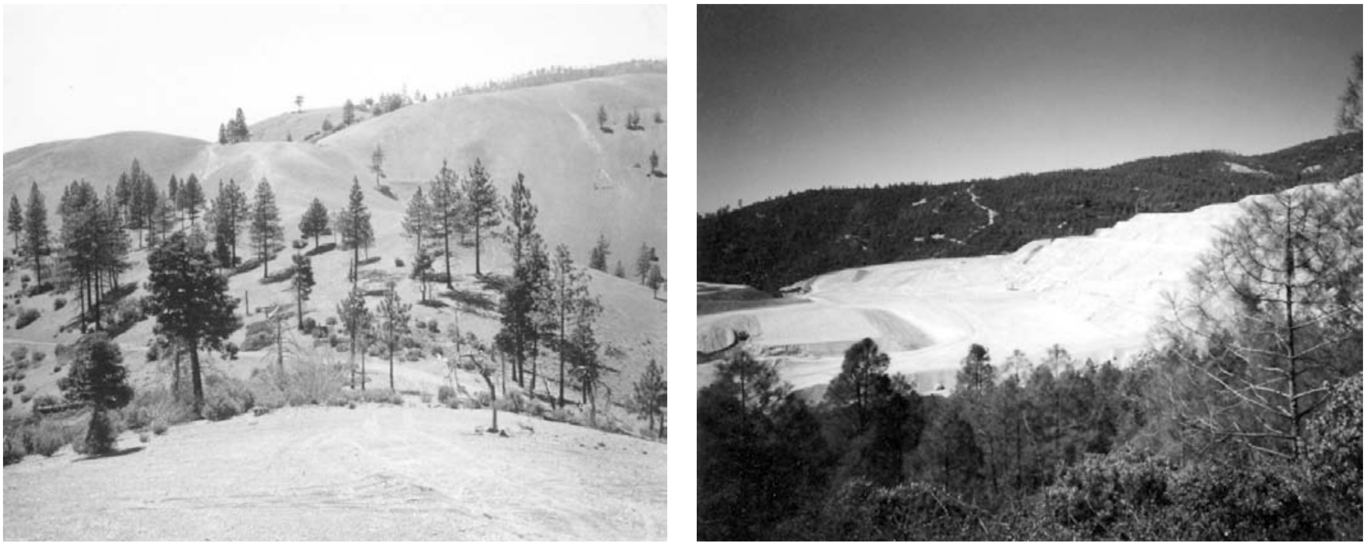
Silica has been shown to be an "essential control on tremolite formation" at various chrysotile deposits, e.g. at the Jeffrey mine in Quebec [18] and elsewhere [29,69]. Silica is also a synthetic requirement for the formation of tremolite [66]. Silica is simply not present in amounts sufficient for tremolite to form at New Idria (Coleman, 1995 pers comm) [29]; also see [69]. This is partly explained by the reduced amounts of silica in the dunite protoliths that gave rise to most of the New Idria deposit [29,69].

Macroscopic and Microscopic Manifestations of Purity

The macroscopic appearance of Coalinga chrysotile ore is unique.[7] It thus resembles, in total contrast to any other form of asbestos, a fine, white laundry powder. This is typically strewn over the surface of the deposit for many square miles creating the appearance of fields of snow (Figure 2).[8] This vast outcropping contains readily-recoverable, relatively pure (>80%) asbestos that can simply be scooped up by hand. The high percentage of readily recoverable asbestos also reflects the purity of the deposit since it results from the absence of extrinsic and intrinsic matrix materials (see below). All other chrysotile ore bodies in the world must be dynamited to recover the chrysotile fibres from the veins contained therein since these are deeply embedded within bedrock. Consequently, the percentage of recoverable chrysotile is, by comparison, very low (max. *c.*15%).

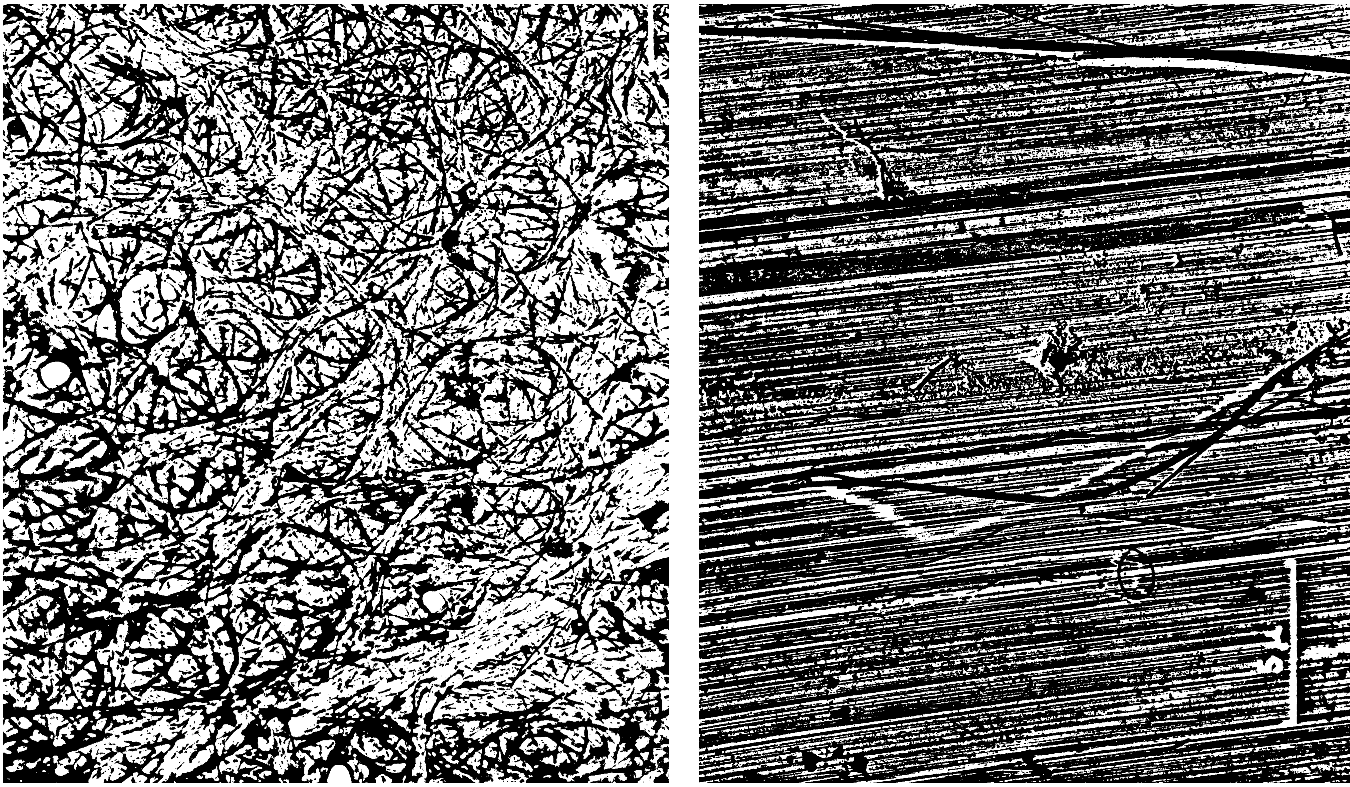
The microscopic appearance of Coalinga chrysotile confirms what is predicted from larger scale observations of this material. Thus, the "typical" Coalinga ore hand sample viewed under the electron microscope has been compared by some to an array of spagetti noodles (Figure 3a). All other forms of chrysotile display a striking parallel fibrillar alignment (Figure 3b). Ultra-high power (×160,000) electron micrographs illustrate why this is so. These beautifully demonstrate the absence of interfibrillar binding material (Figure 4a) in Coalinga chrysotile and its presence in other types of chrysotile (Figure 4b). This has been independently demonstrated by many academic and industrial research centers using a variety of techniques for over 30 years [84–95]; also see [42,75,96–100].

The very great surface area of Coalinga chrysotile has been repeatedly demonstrated to be significantly greater than that of other types of chrysotile [63,75,84–86, 90,101,102] by a variety of techniques (e.g. Differential Thermal Analysis, sulfur dioxide adsorption, theoretical estimates) and is yet another indicator of its extreme purity. This has enabled it to be exploited in the many commercial uses for which it was uniquely suited, e.g. as a binding agent for use in paint, paper, rubber, plastics, resins, fillers and certain cements [66,75,96,103–112] and as a water purification agent (Woollery, 1994 pers comm). Coalinga's high level of purity also made it very desirable for other products, e.g. "clean, white" paper [39,113,114] and electrical board with "good magnetic ratings" [79,98,115,116]. The high purity is related to the fact that Coalinga chrysotile naturally exists as ultra-thin fibrils (Figure 5). Since width and surface area are inversely related, the very high surface area confirms the extremely narrow width of Coalinga chrysotile's fibrils which is consistent with the absence of extrinsic and intrinsic matrix contamination.[9]



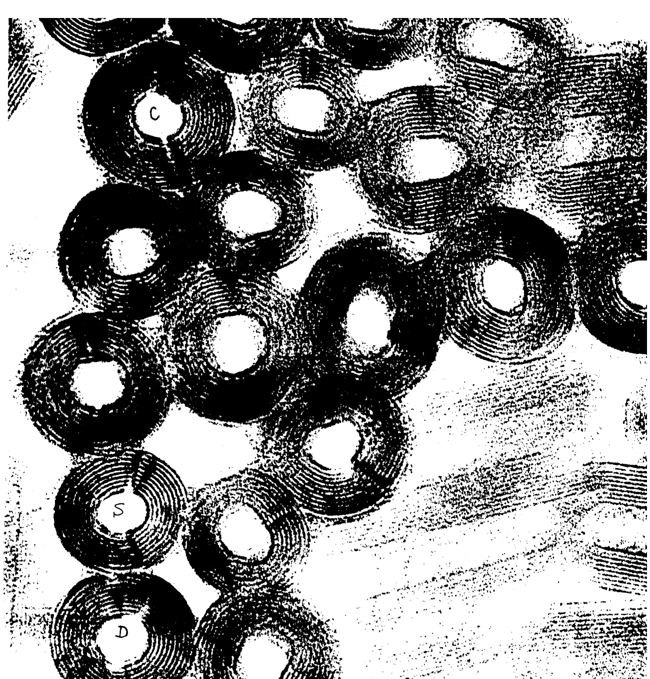
(a) (b)

Fig. 2. (a) The barren landscape of the Coalinga ore deposit; (b) the working face of the KCAC mine.

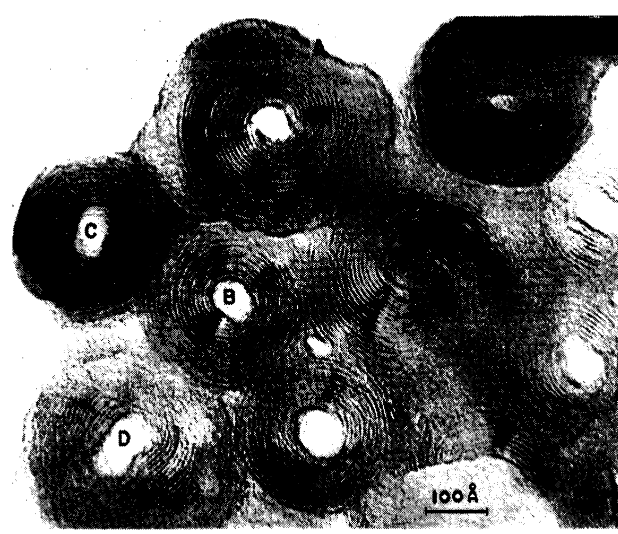


(a) (b)

Fig. 3. (a) Electron microscopic appearance (TEM) of Coalinga ore hand sample displaying random arrangement of fibrils; (b) Electron microscopic appearance (TEM) at the same magnification of non-Coalinga (Canadian-type) ore hand sample displaying parallel arrangement of fibrils. From Chwastiak (1968) with permission.



(a)



(b)

Fig. 4. (a) Ultra high power electron microscopic appearance (TEM, mag. 160,000) of Coalinga chrysotile in cross-section showing absence of interfibrillar matrix; (b): Ultra high power electron microscopic appearance (TEM, mag. 160,000) of Canadian chrysotile in cross-section showing presence of interfibrillar matrix. Bar – 10 nm. From Yada (1971) with permission.

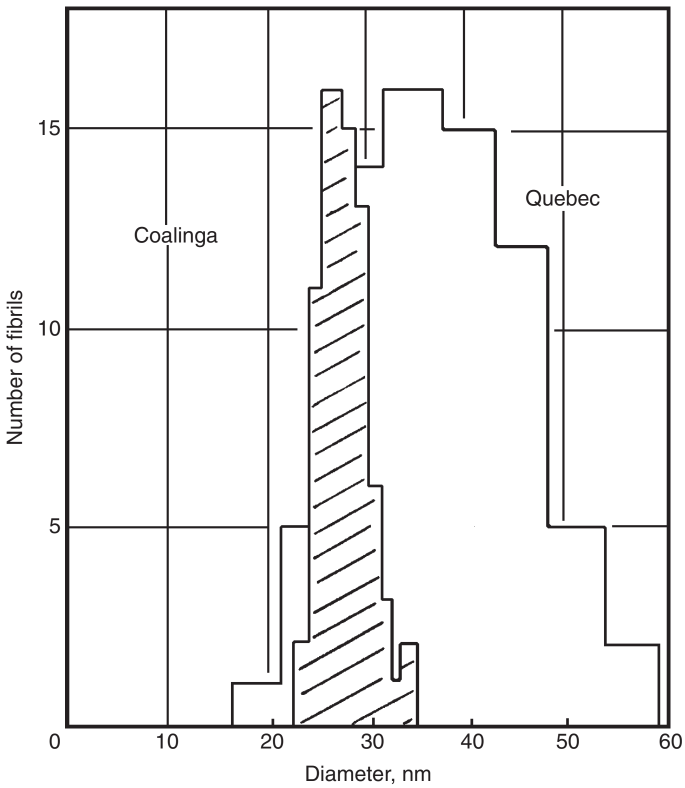


Fig. 5. Histogram comparing fibril widths of Coalinga chrysotile and chrysotile from Quebec. From Chwastiak (1968) with permission.

Inclusions[10] Containing Amphibole-Bearing Rocks are Largely Spatially Restricted to Areas Outside the Ore Zone due to Limited Transport

Normally, tremolite is "spatially restricted to areas outside of the ore zone unless an accident of geology . . . places a tremolite-bearing inclusion in the ore zone or at a site where tremolite can later form", e.g. along a contact zone ([69], p. 215).[11] If this does not take place, "the probability of tremolite asbestos contaminating chrysotile in any deposit is low" [69]. Therefore, "tremolite most often occurs as inclusions genetically unrelated to the serpentine mass" [69].[12] To the extent the "New Idria serpentinite either lacks inclusions or inclusions of appropriate characteristics, asbestos from this deposit is not contaminated by Tremolite" [69]. The inclusions found in the New Idria deposit were originally part of the rocks that surrounded or "mantled" the serpentinite. Rocks from the Fransiscan formation thus mantle the New Idria deposit on the west whilst Cretaceous sedimentary rocks of the Great Valley Sequence bound it on the east [63,69,70].

> "Serpentine is derived mainly from [mantle] peridotite that forms the basement of the oceanic crust. As the oceanic crust is subducted into the trench at the continental margin, slices or slabs of peridotite become immersed in the trench sediments. The water held in the sediments then begins to alter the peridotite to serpentine. This is why the serpentine is surrounded by these trench sediments known as the Franciscan formation" (Coleman, 2004 pers comm).

The extreme forces that gave rise to the ore body also remove rocks from the hanging walls of the mantle and may cause them to become included within the ore zone. As the serpentinite is pushed up from the subduction zone, the serpentine mass may therefore carry with it country rocks[13] that surround and overlay it [24,69].

Isolated tectonic blocks of contrasting rock type may be found throughout the New Idria serpentinite [69]; (also see [29]) but are generally small in size, few in number (see [29] figure 4.14) and very spatially restricted [69]. Since tremolite formation is "a local metasomatic event which has no correlative manifestation on the regional scale" [118], spatial restriction alone greatly limits its presence. Some also believe the inclusions tend to be "welded to the periodite causing them to undergo very little transport relative to the surrounding serpentinite" [65,69] although this view is not universally held (Coleman, 2004 pers comm). The reduction in size of the rocks is also due to a "positive feedback between progressive serpentinisation and the mechanical properties of the rock that leads to effective destruction of the rock fabric". In this, the "New Idria serpentinite may well approximate the end-state" of such physical processes [29]. The amphibole-bearing inclusions that do exist in the New Idria deposit are therefore very rare and generally no more than thin selvages of non-asbestiform tremolite (Coleman, 2001 pers comm). These coverings occur due to the "chemical gradients [that exist] between the serpentinite and the contacts with rocks at the wall". "Chemical reactions between chemically distinct rocks"

> "produce new rocks at the [zone of] contact. These new rocks constitute alteration zones between the serpentine and non-serpentine country rock and result from the movement of chemical components into the serpentinite from the surrounding rocks. . . . A different type of chemical alteration may also occur in zones of broken rock, called shear zones, within the serpentinite. These shear zones can act as conduits through which water carrying dissolved

chemical components may gain access to the serpentinite and chemically alter it. Tremolite can form in this manner".[14] ([69], p. 201)

The movement of calcium from the country rock into the serpentinite can chemically alter the serpentinite and result in the formation of thin rinds of fibrous tremolite in fractures in the rock and the development of scattered pockets of jade [119]. "The contacts between the serpentine and the inclusions are sites of active movement with strong chemical gradients where calcium and silica can be concentrated, resulting in thin selvages of tremolite–actinolite amphibole" (Coleman, 2004 pers comm).

Absence of Tremolite in Chrysotile Deposits that Formed in a Manner Similar to Coalinga

Several other types of chrysotile have formed, at least in part, in a manner similar to Coalinga. These are also characterised by a lack of amphibole asbestos.

Stragari

The Stragari deposit of the Idria region of Yugoslavia is the only other site in the world where large amounts of ore resemble that found at New Idria [25,26]. The resemblance is so strong that the ore body from which Coalinga is mined is called "New Idria" (Mumpton, 1994 pers comm). The macroscopic appearance of Stragari chrysotile has therefore also been called unique [120,121] and has also evolved through excessive shearing forces that produced an ore containing a very high percentage of recoverable asbestos. Whilst there is a pronounced similarity in appearance between the Coalinga and Stragari deposits, some parts of the Stragari deposit also contain a longer grade fibre not found at New Idria. Extensive tests conducted largely by JM [122,123] but also by UCC [124–126]; (also see [127,128]) demonstrated that the Stragari short fibre was comparable to Coalinga and could therefore also be used in similar end products, e.g. floor tile [98]. Not surprisingly, detailed studies showed them to be comparable in terms of surface area, fibre length, compaction strength, color and a variety of performance characteristics [98]. X-ray diffraction analyses [124,128] have also demonstrated that the Stragari wet-processed product exhibited "an [XRD] pattern similar to that of Calidria COF25, UCC's purest asbestos material". "Chemical analyses also showed the Stragari product to have magnesium oxide (MgO), silica (SiO^{2}), and calcium levels almost identical to that of COF25." The XRD, chemical and petrological data therefore also suggest that Stragari is free of tremolite.

Human Observations

Whilst epidemiological data from Stragari could not be found, the possible inclusion of long fibre in the mining and milling of the ore would probably make comparison with the Coalinga workforces impracticable.

Cassiar BC, Canada

The Cassiar deposit formed in a manner similar to New Idria [119], though the former has undergone far less tectonic shearing than the latter. Cassiar is part of the same circum-pacific orogenic belt that extends along the coast of North America from Mexico to the Yukon (Coleman, Mumpton pers comms). The belt represents "a gradation from young, active trench processes with concurrent earthquakes and volcanicity in Mexico and California to more stable land masses in the Canadian Rockies" ([66] p. 126).

The Cassiar deposit was also discovered by accident since it looked so different from other forms of chrysotile. "All of the mines owned by the Cassiar Mining Corporation have a similar geometry. The ore zone is in the middle of the serpentinite and ore occurs as one continuous ore body ([119], see figures 1 and 3). The ore zone is surrounded by a zone of non-ore serpentinite which separates the contact-alteration zones from the ore zone. The ore zones are free of non-serpentine rock types that could provide sites for the development of tremolite"[15] [119].

Ores from the Cassiar deposit are not contaminated by tremolite since these "either lack inclusions, or inclusions of appropriate characteristics" conducive to its formation [69,95,129–131]. This is consistent with detailed direct examination of Cassiar ore [119] and end product that fail to demonstrate the presence of tremolite. Addison and Davies [56] and Addison (2002 pers comm) analysed samples of Cassiar chrysotile by XRD, IR and SEM and failed to find tremolite at a detection limit of <0.0003%. Middleton (1983, unpublished work) analysed four samples of processed Cassiar chrysotile following acid digestion and found trace amounts of tremolite at levels of 0.04% to 0.05%. Most, if not all, of the tremolite in those samples was non-asbestiform (Addison, 2000, 2002). Harris (2000, unpublished work) studied three samples of processed Cassiar chrysotile (Grades AK, AX, and AY) petrographically under polarised light and failed to find tremolite. Butler ([32], table 5.6) analysed at least seven samples of Cassiar ore with XRD and failed to find tremolite in any of them. Others have noted the extreme purity of the Cassiar fibre used in experimental studies [132] (Addison, 2000, 2002 pers comms) and commercial products [77] (van Herle, 1998 pers comm). Cassiar chrysotile was thus one of the cleanest samples ever tested and this enabled it to be used in products such as electrical wire that demanded very high purity [77,133]. Lung burden studies of some Cassiar miners and millers have also failed to reveal amphibole (Enarson, 2000 pers comm, re unpublished studies by Churg).

O'Hanley [131] performed chemical analyses of Cassiar ore and non-ore serpentinite and found calcium at or below the detection limit [0.2 wt.%] in all but 5 samples. Thin section analysis indicated that the calcium in these 5 samples was within carbonate minerals, not in tremolite [131].

Chemical and micro-structural similarities between Cassiar and Coalinga chrysotile further strengthen the notion that these chrysotiles lack tremolite. Thus, both Cassiar and Coalinga fibrils are singly wound spiral or concentric cylindrical layer structures that display marked homogeneity and very narrow width [134]. Structural deficiencies lead to a markedly reduced tensile strength in Cassiar's interfibrillar matrix. This suggests that Cassiar is in a "pre-defibrillated" state [134] in a manner similar to Coalinga chrysotile which is totally defibrillated. The state of defibrillation also probably accounts for the fact that Cassiar [135,136] (Kuntze, 1998 pers comm) and Coalinga chrysotile asbestos are both particularly soluble in acid.[16]

Coalinga and Cassiar also display similarities in chemical composition and patterns of isomorphic substitution ([43], pp. 137, 139; [21,23,32,66,134,139,140]).

Taken together, the aforementioned observations strongly suggest that "as a practical matter, the likelihood that the chrysotile ore could be contaminated by tremolite is nil, being no more than a few ounces of fibrous tremolite in a mine producing several thousands of tons of chrysotile ore daily" [119]. Field observations and studies of mining records also suggest this has always been the case [119].[17]

Health Related Observations Regarding the Cassiar Deposit

Enarson et al. [129] did a respiratory survey of 153 Cassiar miners and millers which included 63 men who had worked in the plant more than 9 years ("exposed group"), 52 who had worked less than 5 years ("controls"), and 38 who resided in the village near the mine. There was only one case of "pleural abnormality" and the incidence (2%) of this finding was in line with that seen in the general population.[18] Enarson et al. [129] suggested that the failure to observe an excess of pleural disease may be related to a lack of amphibole (also see [142]). Morrison et al. [130] found no increase in pleural mesothelioma rates in British Columbia attributable to Cassiar.[19] Gabrielse (2000 pers comm) (also see [143]) studied the Cassiar deposit and said there was no evidence of attributable lung disease in the miners and the millers after almost 40 years of study. The Cassiar Magnesium Company (2000 pers comm) said the "Cassiar mine never had a single asbestos related medical compensation case in its entire 38 year history".

Homogeneity and Potential Sampling Bias

The New Idria deposit is one of the largest mineral deposits in the world. It contains an estimated one trillion cubic meters of serpentine (Coleman, 1994 pers comm). Petrological and mineralogical evidence suggest the deposit is relatively homogeneous and pure throughout. This strongly suggests that sampling bias is minimal.[20] Homogeneity is thus widely reflected in the highly uniform and rather unique appearance of the deposit which has undergone extreme tectonic shearing [25,26] (Mumpton, 2002 pers comm; Coleman, 1994 pers comm). Indeed, "the whole mountain has undergone the same process and is largely defribrillated" (Coleman, 1994 pers comm).

Analytical Limits of Detection

It is highly unlikely that amphibole asbestos has gone undetected at New Idria since sampling strategies and techniques with sufficient analytical sensitivities have been employed in many studies (e.g. see [119]).[21,22]

Visual inspection was frequently a part of the sampling strategies used at New Idria. This has served as an important screen for decades. Chrysotile ore and amphibole minerals differ in appearance and these differences can usually be detected by the naked eye [119]. Many of the larger investigations of the New Idria deposit initially inspected the bench faces of the mines visually. These inspections systematically covered many thousands of acres of the deposit.

Polarised light microscopy with dispersion staining [PLM/DS] was also used in some investigations of Coalinga chrysotile. This method probably cannot reliably detect amphibole levels less than 1%, though some believe the detection limit could be as low as 1 ppm.[23] However, since any amphibole structures contaminating the New Idria deposit would be non-asbestiform cleavage fragments and virtually all amphibole structures derived from cleavage fragmentation are greater than 0.3 μm in width [19], these should be detectable with phase contrast microscopy (LOD < 0.25 um in width).

Petrographic microscopy can probably detect amphibole asbestos at 1 ppm but this would require a point count of more than 500 grains (Coleman, 2004 pers comm).

Visual inspection can overlook fine-grained, disseminated amphibole [18] which would limit its usefulness for detailed systematic screening. However, XRD can be used to systematically screen appropriately large samples. This was the most commonly used method to search for the presence of amphibole in Coalinga chrysotile. Both wide angle range scans for general mineral identification and short range scans to indicate the presence of any specific amphibole mineral phases were used in some studies [28]. A detailed discussion of the LOD associated with the use of X-ray diffraction is beyond the scope of this report but Wicks [31] has discussed this in detail. Wicks believed the LOD in his studies was *c.*1% to 2%. Williams–Jones et al. [18] said amphibole could be "easily detected" by conventional XRD at levels greater than 2.5%. However, Pooley [28] believes the LOD with XRD in his studies was *c.*0.5%. Others believe the limit of detection for XRD is typically at least "several weight percent" though quantitative XRD may reliably determine minerals in amounts less than 1% [144]. Coleman (2004 pers comm) believes that "XRD is not as specific as PCM or PLM methods because the main peaks of the diffraction patterns of minerals present in less than 1% are too diffuse, giving weak patterns that can only indicate that it may be any amphibole which could be fibrous or fracture cleavage flake".

Transmission electron microscopy (TEM) is able to identify the mineral structurally [119] but only XRD coupled with TEM can demonstrate the asbestiform nature of any contaminating amphibole [119]. Moreover, the use of TEM in conjunction with XRD lowers the limit of detection further, e.g. to 0.1% [28]. This has led many to say quantitative TEM is the "state of the art" method since its limit of detection is said to be <0.001% by weight [144]. Acid digestion with XRD–TEM has permitted zones scheduled for mining to be thoroughly screened for amphibole in some Canadian deposits [18] and this combination lowers the LOD still further (to <0.1% [28]).

Lung burden studies are thought by some to be the definitive test of a chrysotile deposit's purity. Some would argue that quantities of tremolite too small to be detected by direct analytical studies of ore may nonetheless bio-accumulate over many years, thus becoming detectable within the lung even when the ore appears to be amphibole free (see e.g. [145]). Therefore, some (Kotin, pers comm; McDonald, pers comm) claim that lung burden studies of long term Coalinga miners and millers would be required to demonstrate definitively the purity of the New Idria deposit. There are strong arguments against this since it is based almost entirely upon analogy with lung burden studies done on the Quebec chrysotile miners and millers. The experience at Quebec and New Idria are vastly different. Tremolite has been recognised as a mineralogical contaminant of the Quebec chrysotile ore bodies for more than 75 years [146,147]; (also see [69,148]). During that time, tremolite, although perhaps found only locally and sporadically in the Quebec deposit, could still be identified without difficulty in many Quebec chrysotile ore samples (e.g. in concentrations ranging from 1% to 5% using conventional techniques) [18,32,149–151]. It could also be found without difficulty in some processed ore samples (e.g. at *c.*1% [32,58] and in air samples taken near residential areas around the Thetford mines at levels many times higher than those seen in urban air [32,149,150]. These were thought to have been even higher many years ago [152,153]. By contrast, amphibole asbestos has never been found in ore, commercial product or air samples from the New Idria deposit using the most sensitive and sophisticated techniques, the most robust, systematic sampling strategies, after examination of many thousands of fibres following nearly 50 years of study.

Health Related Observations

There has never been a formal epidemiological study of the Coalinga chrysotile miners and millers. However, the data that exist are consistent with the absence of asbestos-related disease. Three workforces (JM: $n = 353$; Atlas: $n = 279$; UCC: $n = 456$) mined and milled the New Idria deposit for Coalinga chrysotile from 1960 to 1974. JM and Atlas discontinued working the deposit in 1974 for economic and regulatory reasons. UCC worked the deposit until 1985 and its successor, King City Asbestos Company (KCAC), ceased operations in 2003 for economic reasons. JM and Atlas worked in the Southern part of the deposit whilst Union Carbide mined an area in the Northern section. These were separated by almost 50 miles. Medical records and radiological reports were available for many UCC and JM[24] workers. None could be found for those that worked at Atlas. Detailed review of the medical records available for the UCC, KCAC and the JM workers revealed no evidence of attributable, asbestos-related disease[25] [7,9,10]. Discussions with representatives of all of these companies, including the Atlas Corporation, failed to reveal any asbestos-related compensation claims.[26] A demographic study of the incidence of mesothelioma in the area around New Idria also failed to demonstrate an excess of this disease (Mills, 2002 unpublished Case Control analysis from the Calif. Ca Reg.).[27]

Sponsorship of the Studies Cited in this Review

The analytical studies of Coalinga chrysotile described at the beginning of this review (see "Direct Evidence") have been sponsored by industry (e.g. Union Carbide [25, 28], JM and Eternit), academia (e.g. Mt. Sinai [27], Georgetown University [41], Harvard University [29], and Stanford University [20]) and government (e.g. the USGS, EPA IX and others [21–23; 30]). Only two were done solely in the context of litigation [27,28] and, whilst done for "opposing" sides, both failed to find tremolite. Historical mineralogical reports of the New Idria district have also been examined by others (Van Balen, 2001 pers comm; Coleman, 2000 pers comm) and none has ever recorded the presence of amphibole asbestos.

Regulatory Conclusions

Various US Agencies have concluded that the New Idria deposit contains exclusively chrysotile. The Agency for Toxic Substances Disease Registry (ATSDR) [158] has said that "only chrysotile is of importance to the Atlas and the JM Coalinga mill site". Woodward Clyde Consultants [30] under contract to EPA Region IX prepared an inventory of potential asbestos sources in the New Idria Coalinga Study Region for the Atlas and the Coalinga Superfund Sites ([30], US EPA Contract: 68–01–6939; Doc. No. 239-RI1-RT-EYJX: 15 September 1987, Appendix A) and stated: "Chrysotile asbestos is the only asbestos mineral found in the (New Idria) region."

Conclusions

Direct analytical studies using the most sensitive methods, conducted over almost 50 years, have failed to find amphibole asbestos in Coalinga chrysotile. Very rare examples of amphiboles have been found in the New Idria region but these were not asbestiform, located outside the ore zone in very limited, narrow zones, selvages, or mono-mineralic rinds most commonly found along the outer rims of tectonic blocks. The chance that these could contaminate the mined ore or become incorporated into milled Coalinga chrysotile is extremely remote. If it ever occurred, incorporation into milled ore would result in a level of contamination amounting to less than a few ounces of amphibole in many thousands of tons of chrysotile. Moreover, the non-asbestiform nature of the amphiboles means they would lack biological potential [19] and be of no biological consequence.

Indirect evidence related to the manner in which the New Idria deposit forms and the physical and chemical determinants of tremolite largely explain why Coalinga chrysotile does not contain amphibole asbestos and also why tremolite does not naturally contaminate all chrysotile deposits.

Further evidence that Coalinga chrysotile does not contain amphibole asbestos comes from human observations of workforces that mined and milled this material and of populations living on and near the ore body. To date, there has not been any evidence of an attributable excess of pleural plaques or mesothelioma in any of these individuals. Since pleural plaques and mesothelioma are causally associated with exposure to amphibole asbestos [3,6,142], their absence is therefore also consistent with the view that Coalinga chrysotile is not contaminated by asbestiform amphibole.

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Valuable discussions were also held with Senior EPA IX Coalinga Superfund managers; former corporate officials, company workers, miners and millers from Union Carbide, KCAC, JM and Atlas; carriers for and successors to the Atlas corporation; former senior JM scientists and physicians; former and current King City and Coalinga medical center physicians, radiologists and pathologists; the Monterey Air Resource Board Director and Staff; and numerous other agencies both within and outside of California including the California Bureau of Land Management, California Air Resource Board, the California Fish and Gaming Commission, the California Mining Association, the California US Bureau of Mines, the California Occupational Safety and Health Authority, the Deputy Director of the California EPA, the California Dept.of Forestry; California Dept. of Water Resources; the California Dept. of Health Services; the California Dept. of Parks and Recreation; the Coalinga City EPA; the Dept. of the Interior for the Pacific SW Region; PTI Environ. Services Inc. acting as Risk Assessment officers for the BLM; the Southern Pacific Railroad; and the US and California Geological Surveys. Thanks also are due to the Union Carbide, the Johns Manville and the The Cassiar Magnesium Companies for allowing me to review the various documents cited herein.

Finally, the invaluable assistance of Professor Robert Coleman is kindly acknowledged for discussions spanning over 10 years. As indicated in the review, Professor Coleman's contributions to our understanding of the formation of the New Idria serpentinite in relation to plate tectonics have been enormous and unparalleled, starting in research efforts that began nearly 50 years ago. Acknowledgment as indicated above does not mean that the individuals cited concur with the conclusions and opinions expressed in this report, which are my own.

Notes

1 The Gem Mine is located near the headwaters of the San Benito River on the western flank of Santa Rita Peak. The mineralised zone was 520 ft. long and about 400 ft. wide in its widest part. Within that zone, the benitoite-bearing rocks were only 64 ft. wide and 400 ft. long. The mafic schist is interpreted as Franciscan rock entrained within the serpentinite ([29], see pp. 4–84 and 4–90). It is totally removed from the ore body. "The altered wall rock" of the gem mine also contained "cavities filled with amphiboles, in a felty texture" and other areas with "abundant amphibole needles" ([29], see pp. 7–12).

2 Nonetheless, the differences that exist between COF25 ands RG144 are very small and biologically inconsequential.

3 "Serpentinites are lens-shaped bodies that consist of rocks primarily composed of serpentine minerals. The (chrysotile asbestos) ore zone of the serpentinite contains greater than 3% chrysotile fibre by volume. "Non-ore serpentinite" rocks contain less than 3% fibre. Collectively, these are called "country rocks" and they enclose the serpentinite ore zone [119].

4 Tremolite formation may occur at very low temperatures [18] but these conditions are not found at New Idria [29]. Thus, tremolite forms at low temperatures at the Jeffrey mine in Quebec [18] because the serpentinising fluids in the eastern townships of Quebec are rich in calcium carbonate (Ca CO3). However, those at New Idria are low in Ca CO_3 which thereby inhibits tremolite formation ([29], pp. 3–7, 3–26, 3–73, 4–64).

5 Traces of talc were reported in some JM samples (Strieb (pers comm) cited in Mumpton and Thompson [25]). However, Mumpton and Thompson [25] said these were "not typical of the main [ore] body". IITRI and the BUM also reported talc ([44] table 16; [43] table 6.1, pp. 20, 61) and calcium ([44] tables 1,3; [43] tables 6.1 and 7.7, p. 84) in some Coalinga samples. However, XRD failed to confirm the presence of tremolite. Bright ([24] p. 12) also claimed that talc was present in "rock free areas", sometimes in large amounts ([24] pp. 14 and 15) and occasionally in a fibrous form ([24] pp. 15 and 16) but the validity of this claim has been questioned by Mumpton and Thompson [26]. Mumpton and Thompson [26] said talc was reported in Coalinga ore by others: (anonymous, 1957 cited by [26]; Miller, 1960, cited by [26]). However, this could not be "confirmed in any of the several thousand samples examined [by them]" (cf: Table 3 and p. 135). Mumpton and Thompson [25,26] also reported calcium in some Coalinga ore samples, e.g. as CaO [26] cf: tables 2, 4, and 7; as Calcite [26] cf: p. 137, and [25] pp. 65 and 73, but the XRD findings ruled out the presence of tremolite.

6 Amphibole-group minerals are effectively absent from the chrysotile-bearing serpentinite ores: only one of 175 chrysotile-bearing samples analysed using X-ray diffraction contained detectable tremolite (>0.1 wt.%, <2.5 wt.%)" [18]. Tremolite asbestos was only found in one of 128 chrysotile samples from different parts of the world in another extensive investigation [32]. In yet another study [71], tremolite was only noted in one of 58 chrysotile samples examined with XRD.

7 Its appearance is so unusual that, despite the immense size of the New Idria serpentinite ore body (an estimated 50 square mile area extending nearly 6 miles deep with a total estimated volume of approximately 6 trillion cubic meters: Coleman, pers comm), it was not recognised as commercially utilisable asbestos until the mid-1950s [73,74,78] and see [75] for discussion of commercial history and related subjects.

8 Some experts say the New Idria serpentinite is the largest slip fibre chrysotile deposit in the world (Hodgson, 1988 pers com,). For clarification, slip fibre arises from cross fibre that has been "subjected to intensive folding or shearing" ([66,76,77], p. 120) causing some to believe that it is "inherently weak and brittle" [77]. There are several other nearly pure deposits of "slip" fibre including the former Carey Canada mines in the East Broughton area of Quebec ([32], pp. 48, 49, 76, 77) and the Balangero mine in Northwest Italy. Balangero is thus said to be an occurrence "similar to that found at East Broughton" [76] where, in both sites, there is a general lack of intrusions ([32] p. 51; [76]). Thermogravimetric studies have not only been said to support the slip fibre nature of the Carey deposit but also suggest a similarity between Carey and Coalinga chrysotile fibre ([32], p. 180). Johns Manville also conducted a series of comparative studies between Coalinga and Carey chrysotile [31,79,80–82]. Chemical and X-ray diffraction studies of Carey ([32] table 4.1, 4.4, 4.8, 4.9, 5.5, 5.6, pp. 153, 179; appendix 2, figure 6.6) and Balangero ([32], table 4.9, appendix 2, figure 6.6) chrysotiles suggest these are also free of tremolite. It may also not be totally co-incidental that very high nickel levels have been found in samples of Balangero [83], Cassiar [66,83,119] and Coalinga [66] chrysotile.

9 The JM and UCC Coalinga samples contain very low concentrations of accessory minerals such as magnetite that commonly contaminate other

chrysotile ore bodies. Moreover, at the mine, the ore is purified further through screening [28,98] whilst additional purification takes place during the milling process [25,26,28,75]. The wet method used by Union Carbide may have been more efficient than the dry process used by JM and Atlas [98]. Thus, the wet process [117] would have been able to remove tremolite, if indeed any had been present, more efficiently than the dry process, which is suggested by the fact that the calcium levels in wet ore samples [25] were less than those in "refined Coalinga chrysotile" ([75], see table V, pg. 20).

10 "Included" rocks are also referred to as "inclusions" and "dykes". The five types of amphibole present in the Jeffrey chrysotile mine all occur in, or adjacent to, felsic dykes which control the distribution of the bulk of the amphibole in the deposit. There, tremolite occurs as narrow (<1 cm wide) shear and extensional fracture-fillings in pyroxenite. These veins typically comprise between 1% and 5% of the volume of the rock and host most of the asbestiform amphibole [18].

11 The boundary between the serpentinite and the "country rock" is known as the "contact zone" [119]. Amphiboles may form at contact zones between tectonic blocks [29] also see [69]. Thus tremolite could have been found at New Idria on isolated rodingite inclusions [69] also see [29], however, such areas very rarely, if ever, occur in the New Idria ore zone.

12 The "serpentinite is not related genetically or kinematically to either the foot-wall or the hanging-wall rocks that bound it. Therefore, since the country rocks contain or facilitate the formation of tremolite, the fact that they are not genetically related to the ore zone largely explains, by inference, why tremolite is not normally present" (in the ore zone) [69].

13 The (New Idria) serpentinite is known as a "mantled dunite" [69].

14 Not surprisingly, a very large amount (over one million tons) of "Coalinga type asbestos" has recently been discovered nearby the Cassiar pit (Kuntze, 1998 pers comm].

15 Detailed analyses of the Cassiar mine [119,131] showed that minerals potentially contaminated with tremolite were restricted to the contact-alteration zones outside of the serpentinite and thus outside of the ore zone. Neither the non-ore zone serpentinite nor the ore zone was found to contain any type of amphibole [119]. Tremolite has been identified in samples near the boundary of the Cassiar ore zone using thin section analysis [131]. However, the tremolite was found to be acicular rather than asbestiform [131]. X-ray and electron microprobe analyses have confirmed the presence of asbestiform tremolite-actinolite in 4 small locations in the Cassiar mine but none was identified in the ore zone [131]

16 Increased solubility and Coalinga's short fibre length easily accounts for its markedly reduced half-life in vivo [137] compared with standard Canadian chrysotiles [138].

17 Rickards (2000 pers comm) thought that the historical data might be too old and unreliable for this type of assessment.

18 It is not clear if this was a case of pleural plaque (which could been related to amphibole exposure [141]) or pleural thickening (that would have no such association). This study was also hampered by high turnover and small size.

19 A large collaborative, industry-wide, lung cancer screening study done under the supervision of Dr Sverre Vedal at the University of British Columbia included two groups of long term Cassiar workers. The findings of this study remain unpublished (Vedal, 2000 pers comm; Enarson, 2000 pers comm).

20 The Californian Geological Survey [144] has stated that no exact guidelines exist for determining the number of specimens that need to be collected and concluded that statistics from analyses of specimens cannot always be said to be representative. It also describes a variety of "Naturally Occurring Asbestos Sampling" strategies and different methods for conducting these types of investigations.

21 Detailed mapping, core logging, exhaustive mineralogical and geochemical studies, and a theoretical evaluation of the stability relations of amphibole-group minerals and other species in the system CaO–MgO-SiO_2–H_2O enabled the environment of amphibole crystallisation of the Jeffrey open pit to be reconstructed and the origin of the amphibole contaminant in the ore to be determined [18].

22 Unequivocal identification of asbestos materials requires information on morphology, chemical composition, and crystal structure. The primary methods used by commercial asbestos labs are PLM and TEM. [144]. Electron microprobe analysis yields the chemistry of the mineral and, together with the X-ray analysis, allows the mineral to be named. Thus, X-ray diffraction can indicate that the fibre is an amphibole, but whether or not it is, say, tremolite or actinolite, is based on the chemistry of the mineral, which is obtained by using the electron microprobe [119]. Chemical analyses can indicate how much calcium is present in each sample and thin section petrographic microscopy can determine the mineral in which the calcium occurs in samples that contain more than trace amounts of calcium. Since tremolite is a calcic amphibole, the "host rock must contain calcium for it to form" [69]. Failure to find calcium excludes the presence of tremolite. This is true even when calcium is present in small amounts since calcium is conspicuous in thin section as its optical properties are totally different from those of the host minerals [119].

23 Chatfield (pers comm) described the difficulties in assigning a specific LOD to PLM with oil immersion. However, Addison (pers comm) believes it is possible to work to a limit of 1 ppm with PLM on the assumption that it would be possible to find the weight equivalent of a single, 5 µm long, 1 µm wide, amphibole fibre in one milligram of chrysotile. Chatfield argues that this depends greatly upon the counting medium and nature of the original sample. If, for example, the sample was not properly homogenised or loaded with large amounts of other non-asbestos material that produced pseudofibres, e.g. vermiculite scrolls, the LOD would be far greater than 1 ppm and may even approach 1.0%. The Californian Geological Survey [144] says that the practical resolution of PLM / DS is *c.*1 µm.

24 Some senior JM Coalinga workers brought down from JM Canada to work at Coalinga had also incurred significant exposure to Canadian long fibre chrysotile prior to coming to California.

25 Egilman [154,155] has claimed that there is an excess of attributable cases of asbestosis and lung cancer in the UCC/KCAC workforce. A full discussion of his claims will be dealt with elsewhere [Ilgren, 2004 in prep]. Here it can be said that none of the cases alleged by Egilman to be due to exposure to Coalinga chrysotile are bone fide. Indeed, there has never been a bone fide case of asbestosis or lung cancer in this work force (also see [9]).

26 Numerous experts were consulted regarding potential human health effects. These included, but were not limited to, Professors Clark Cooper, J.C. McDonald, R. Balzer, and Wm. Rom; Senior EPA IX Coalinga Superfund managers; former corporate officials, company workers, miners and millers from Union Carbide, KCAC, JM and Atlas; carriers for and successors to the Atlas corporation; former senior JM scientists and physicians including Mr Wm. Streib, Wm. Reitze, Fred Pundsack and Dr Paul Kotin; former and current King City and Coalinga medical center physicians, radiologists and pathologists; the Monterey Air Resource Board Director and Staff; and numerous other agencies both within and outside of California including the California Bureau of Land Management, California Air Resource Board, the California Fish and Gaming Commission, the California Mining Association, the California US Bureau of Mines, the California Occupational Safety and Health Authority, the Deputy Director of the California EPA, the California Dept.of Forestry; California Dept. of Water Resources; the California Dept. of Health Services; the California Dept. of Parks and Recreation; the Coalinga City EPA; the Dept. of the Interior for the Pacific SW Region; PTI Environ. Services Inc. acting as Risk Assessment officers for the BLM; the Southern Pacific Railroad; and the US and California Geological Surveys.

Only one claim by a former UCC worker has been made in relation to Calidria exposure. A former employee working in the KCAC mill thus alleged in September, 2000 that he suffered from asbestos-related pleural disease due to exposure to Calidria. However, in May 2002, he voluntarily dismissed the case against UCC.

27 Yano et al. [156] claimed that amphibole free chrysotile could cause mesothelioma. However, Tossavainen et al. [157] noted that the Chinese chrysotile under study was contaminated with tremolite.

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