UNITED STATES DEPARTMENT OF INTERIOR

GEOLOGICAL SURVEY

REVIEW OF THE GEOLOGY AND SHALE-OIL RESOURCES OF THE TRIPOLITIC OIL-SHALE DEPOSITS OF SICILY, ITALY

by

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Introduction

At the invitation of Mr. Raymond C. Rex, Jr., Research Director of Hycrude Corporation, a subsidiary of the Institute of Gas Technology (IGT)--a non-profit corporation headquartered in Chicago, Illinois, I traveled to Sicily, Italy, in June 1987 to examine the Miocene oil-shale deposits of Sicily. The purpose of my visit was to familiarize myself with the geology and the resource potential of these deposits and to determine whether it would be worthwhile to recommend a project to evaluate the economic resources of the deposits in cooperation with the Sicilian government, Hycrude Corp., and the U.S. Geological Survey.

Mr. Rex and I spent four days in Sicily. On the first day, Tuesday, June 9, we reviewed the geology of the oil-shale deposits at the offices of Ente Minerario Siciliano (EMS)--the Sicilian Minerals Agency, a unit of the Sicilian government--in Palermo with geologist Dr. Nicolo La Rosa. Dr. La Rosa showed us geologic maps of the oil-shale area and lithologic logs of drill cores of the deposits from recent drilling by EMS. We also met with Dr. Giuseppe Midiri, president of EMS, to discuss the possibility of a joint study. On Wednesday, June 10, we examined outcrops of oil shale at five localities in the Sicilian basin in the central part of the island accompanied by Dr. La Rosa and Dr. Pier Antonucci of the University of Messina. Several samples were collected for study in Denver. We also visited a small oil-shale mine that was operated by the German armed forces during WWII. On Thursday, June 11, Mr. Rex and I visited chemists Drs. Rosario Maggiore and Giovanni Schembari at their laboratory at the University of Catania (Catania, Sicily). These workers analyzed a number of samples of the EMS oil-shale cores under contractual arrangement with EMS. We were given a copy of the results of their work (Maggiore, 1987?). While at the university, I briefly examined portions of the EMS cores and collected several samples. On the last day of our stay in Sicily, Friday, June 12, we met with Professor Nicola Giordano, Director, Institute of Energy Transformation and Accumulation (Istituto Trasformazione e Accumulo Energia), National Research Council (CNR-TAE), in Messina to discuss logistical problems of working in Sicily. Professor Giordano explained that he would act as an intermediary to expedite and coordinate work between the USGS, Hycrude Corp., EMS, and other Sicilian agencies that might be involved in a cooperative study. During our travels in Sicily, we were treated with great hospitality and our Sicilian counterparts were most cooperative and open in our discussions.

In this report, the geology of the tripolitic oil-shale deposits is summarized on the basis of my observations while in Sicily, on a few analyses that I made on samples of the oil shale, and on a review of the literature. Recommendations are made on what further studies might be made to evaluate the economic potential of the deposits.

The terms "tripoli" and "tripolite" are used throughout this report in deference to their longtime usage to describe the Miocene oil shales of Sicily, whereas "diatomaceous marlstone" and "diatomite" may be more accurate descriptors. Lithologic terminology of these deposits is left to others.

Oil-shale developments

Although the tripolitic marlstone beds have been prospected for many years, the only known production of shale oil was from a small mine near Serradifalco (figs. 1,2,3, and 4) which was operated by the German military forces for two years during WW II (Dr. N. La Rosa, per. comm., 1987). During the past several years, permits have been issued by EMS to Agip Minerals to explore the tripolitic beds by drilling. Several bore holes have been drilled by the company; however, the cores were not available for inspection, nor have the exploration data been released, other than information on total carbon reported by Maggiore (1987?) for one of the wells located near Serradifalco.

In 1983-84 EMS drilled four exploratory holes into the Tripoli formation near the village of Villarosa in the northern part of the Sicily basin (fig. 5). The locations of the Villarosa core holes are in an area of the Sicily basin where the basin-center sequence of tripolitic rocks grades laterally toward the northern basin margin into a dominantly marl sequence (Monnier, 1978, fig. 13). The Villarosa core holes were drilled apparently north of the thickest part of the tripolitic facies which lies roughly along a line between Canicatti and Barrafranca (Monnier, 1978, fig. 3).

Previous studies

The tripolitic oil-shale deposits of Miocene age of Sicily have been known for a long time, but relatively few stratigraphic and geochemical details were known about them until two papers were recently published, one by Palmer and Zumberge (1981) and the other by Broquet and others (1984). Palmer and Zumberge (1981) studied the geochemistry of 17 samples of oil shale and associated rocks from seven localities in the Sicily basin (fig. 5) using X-ray diffraction, Rock-Eval, and gas chromatrography/mass spectrometry. These workers concluded that the oil shales were deposited in a marine environment and the kerogen is of algal and bacterial origin. The Sicilian kerogen has a high atomic H/C ratio comparable to that of the Green River oil shales of western United States and is thermally immature.

Broquet and others (1984) summarize a doctoral thesis by M. Monnier (1978) who made an excellent detailed field and laboratory study of the petroleum potential of the tripolitic deposits in the the Sicily basin (fig. 5). According to these workers, the tripolitic deposits consist of a sequence of interbedded marlstone and marly tripoli of marine origin which reaches a maximum thickness of 45 m in the center of the basin. The petroleum potential (oil and combustible gas) for fresh tripolitic rocks having a production potential of 64 to 114 kg of hydrocarbons per metric of rock is estimated to be 7-12 billion metric tons (about 51-88 billion barrels of oil equivalent) for a 3,000 km^2 of a less tectonically disturbed part of the Sicily basin. A petroleum potential of 23 billion metric tons (about 169 billion barrels of oil equivalent) is estimated for the entire basin area of 6,500 km^2. Tmax temperatures of the kerogen were found to range from 300° to 400° C indicating immature kerogen as reported by Palmer and Zumberge (1981). These workers conclude that kerogen is largely of marine algal origin and that blobs and seeps of bitumen-like material found at some localities (e.g., at the Cozzo Disi sulfur mine near Casteltermini) are a kind of a protokerogen, rather than a true bitumen, derived locally from the tripolitic beds.

Dr. Rosario Maggiore and coworkers at the Department of Chemical Science, University of Catania, made elemental analyses of samples of the tripolitic deposits from the three core holes drilled by EMS near Villarosa and from a well drilled by Agip Minerals near Serradifalco. Maggiore (1987?) found that most of the Villarosa samples contained less than 1 percent organic carbon by weight--too low to be of economic significance. Only total carbon was reported for the Serradifalco samples, however, histograms of total carbon and hydrogen (fig. 6) show that both elements are considerably higher in the Serradifalco samples than in the Villarosa samples. A higher carbon content could be due to an increase in carbonate minerals, however, the fact that both carbon and hydrogen are higher in the Serradifalco samples, suggests that the organic content is also appreciably higher than in the Villarosa samples.

The studies by Palmer and Zumberge (1981) and Broquet and others (1984) suggest that the tripolitic deposits have some potential as a shale-oil resource. The high hydrogen content of the kerogen reported by Palmer and Zumberge (1981), the presence of bitumen-like seeps, and the rapid oxidation of the kerogen in surface exposures suggest a kerogen of unusual chemical character that may make it easier to retort for shale oil than other types of oil shales.

The resource figures presented by Broquet and others (1984) are based chiefly on analyses of surface, or near-surface, samples which these workers concede are degraded owing to weathering and oxidation of the kerogen. Accurate estimates of shale-oil resources will require drilling core holes and analysis of samples. Assuming that an oil-shale resource of sufficient size and grade is found, the most economical method of shale-oil recovery will depend on the local geologic structure, groundwater conditions, and the amount of overburden that is present.

Geologic setting

The following notes on the geologic history of the Sicily basin were abstracted from Monnier (1978), Palmer and Zumberge (1981), and Broquet and others (1984).

The Sicily basin (identified as the Caltanissetta basin by Monnier, 1978, and Broquet and others, 1984) occupies an area of about 6,500 km^2 in south-central Sicily and it extends southwestward into the Mediterranean Sea (fig. 5).

The Sicily basin was formed by tectonic emplacement of a series of nappes (nearly flat sheet-like units of rock formed by thrust faulting and/or recumbent folding) during Tortonian (early late Miocene) time. Initially, when the basin was open to the Mediterranean Sea, deep-water marlstones were deposited in the trough of the basin while carbonate reefs formed along the shallow parts of the basin margins. Later, during Messinian (late late Miocene) time, the basin became restricted. Evaporative conditions began to develop within the basin and the basinal waters became stratified. Algae, diatoms, and other marine organisms flourished in the nutrient-rich, oxygenated, upper basinal waters. The remains of these organisms accumulated with tripolitic marly sediments under anoxic conditions at the bottom, and were preserved as kerogen-rich, tripolitic marlstones--the oil shales of the Tripoli formation found today in the Sicily basin (fig. 7).

Under continuing evaporitive conditions during the Messinian, the basinal waters became more saline, and carbonate sediments with disseminated crystals of salt (Basal limestone formation) were deposited on the tripolitic sediments. The waters of the restricted Sicilian basin reached their maximum salinity during the "Mediterranean Salinity Crisis" during which time an evaporitic sequence of gypsum, halite, and locally, potash salts, was deposited. Calcareous marlstones with abundant remains of Globigerinid forams ("Trubi" of local useage) were deposited on the evaporite beds, marking the return to normal deep-water marine conditions within the basin. A mixed assemblage of marine and continental sediments of Pliocene and Quaternary age was deposited on the Trubi beds. Uplift and emergence of the Messianian rocks, with concomittant folding and faulting, has locally exposed the tripolitic marlstones, typically in small synclinal structures, within the basin.

The Tripoli formation, the Basal limestone, and the upper gypsum and salt sequence ("gessarenite beds") form collectively an evaporite series ("Gessoso solfifera series" of local useage). Kerogenous rocks capable of producing oil by pyrolysis are found in the Tripoli formation. The gessarenite beds contain rock salt in sequences as thick as 700 meters which were deposited in local sub-basins in the Sicily basin (Agrigento Geologic Map 636). Commercial deposits of native sulfur and potash are found in the evaporite series.

Underlying the Tripoli formation is a sequence of claystones, sandy claystones, and sandstones of late Tortonian age which rests unconformably upon the Tortonian "clayey complex"--a sequence of highly contorted clayey beds containing indistinct patches and blocks of marly and clayey sediments and basalt (olistostromes) ranging from Cretaceous to Miocene in age (fig. 7).

Tripoli formation

According to Monnier (1978), the Tripoli formation ranges from a featheredge to a maximum measured thickness of 45 meters near Barrafranca (fig. 8) in the center of the Sicily basin. However, the thickness of the Tripoli formation in three EMS core holes drilled near Villarosa reportedly ranges from 62 to 95 meters. Possibly, different contacts were picked for the formation in the subsurface by EMS. In places where the formation is absent due to nondeposition or erosion, the overlying evaporitic rocks lie directly on the Tortonian clayey complex (Agrigento Sheet 636). Thus, the Tripoli formation is not fully coextensive with the boundaries of the Sicily basin. Figure 9 shows the thickness of only the tripolitic beds in outcrop sections that were measured by Monnier (1978, p. 13-25). The trend of maximum thickness of the tripolitic beds extends from near Barrafranca where the tripolitic rocks reach 25.4 meters in thickness southwestward to Favara (near Agrigento) where the tripolitic strata measure an aggregate thickness of 15 meters. The isopachs of the tripolitic beds (fig. 9) suggest two depositional centers; one near Barrafranca and the other near Favara. The tripolitic rocks grade laterally into marls toward the basin margins (Monnier, 1978, figs. 13 and 14).

Although the Tripoli formation forms poor outcrops, it can be seen in small ledges, landslide scarps, and roadcuts at numerous places within the Sicily basin. The formation is composed of interbedded grayish green marlstones, brown claystones, and marly tripolis. The marlstones are laminated and occur in meters-thick beds. The claystones are typically fissile, are in beds rarely exceeding 10 cm, and consist of montmorillonite, kaolinite, and mixed-layer clays in relatively constant proportions. The tripolis (diatomites) are composed of 60-70 percent of silicous fragments of diatoms and radiolaria with lesser amounts of calcite or dolomite and kerogen (figs. 13 and 14). Polished specimens of tripolitic marlstone from the open pit at the Cozzo Disi sulfur mine revealed much interstitial pale orange-fluorescing organic matter (probable bituminite), sparse vitrinite or inertinite, and much finely disseminated pyrite under UV reflected light.

Broquet and others (1984, fig. 2) point out that the Sicilian tripolis are distinctly more marly than the diatomites of the Miocene Monterey Formation of California. It should be also be noted that the Monterey diatomites contain notable quantities of uranium in association with organic matter (Durham, 1987). For this reason, six samples from the Sicilian deposits were analyzed for uranium by neutron activation. These samples were found to contain from 2 to 11 ppm uranium with Th/U ratios ranging from 0.50 to 2.4, suggesting that uranium has been concentrated to some extent in the tripolitic rocks in the Sicily basin (R.A. Zielinski, oral communication, 1988).

The upper part of the Tripoli formation contains laminated limestone and dolomite. In places, the carbonate beds contain small cubic cavities after halite indicating the increasing degree of salinity of the basinal waters during deposition of the Tripoli formation.

Figure 10 shows four north-south structural cross sections of the Tripoli formation and associated rocks in the Sicily basin. Much of the Tripoli formation is found in small, commonly faulted, synclinal structures. In parts of the basin, the formation is buried 900 or more meters below the surface. Locally, such as at the Cozzo Disi mine (fig. 11), the formation is strongly folded. In other areas, such as at the oil-shale mine near Serradifalco and near Villarosa (fig. 12), the formation is relatively little disturbed. The grade of oil shale, the depth of burial, and the degree of structural deformation will have an important bearing on the mineability of the tripolitic beds.

<u>Kerogen</u>.--In fresh exposures, the tripolitic marlstones are typically brown to grayish black owing to their kerogen content. On the outcrop where the kerogen is oxidized, the tripolitic rocks weather to white ledges.

Broquet and others (1984) noted that the kerogen is found in the clayey fraction of the sampled rocks and it is composed largely of amorphous, brown, colloidal material that contains abundant muriform spheres of pyrite resembling certain forms of bacteria. A carbonaceous fraction of inertinite is also present. Black, viscous globules of a bitumen-like substance can be seen in thin section. This tarry substance migrates along fractures into the overlying Basal limestone and, at the Cozzo Disi sulfur mine, it is abundant enough to impede mining operations. Tmax temperatures of 320 to 400° C from Rock-Eval analyses (See Tisot and Welte, 1978, for a brief description of the Rock-Eval method.) indicate a very immature kerogen. The S2 peaks from Rock-

Eval analyses of outcrop samples are typically truncated, indicating partial decomposition of the kerogen, perhaps by bacteria. Plots of the S2 and S3 data on a Van Krevelen diagram indicate a type I kerogen of largely algal origin having an excellent petroleum potential.

Shale-oil estimates

Few, if any, Fischer assay determinations have been published on the Sicilian oil shale deposits. However, Monnier (1978, table 10) and Palmer and Zumberge (1981, table 4) published Rock-Eval data for a few samples from the Sicilian basin from which estimates of shale-oil yields can be made.

A correlation of Fischer assay with Rock-Eval analyses for a group of 69 samples of oil shale collected from deposits of different ages and geologic settings from around the world is shown in fig. 15. About 88 percent of the variation in the sum of S1 and S2 from the Rock-Eval data is "explained" by the Fischer assay determination. Using the equation derived from these data, the estimated Fischer assay yields for a group of 27 samples from the Sicily basin collected from the Tripoli formation by Monnier (1978, table 9), Palmer and Zumberge (1984, table 4), and by the U.S. Geologcial Survey are listed in Table 1. Not all of the samples are of tripolitic rocks, but include shale, dolomite, and anhydrite. Estimates of shale-oil yields range from 8 to 125 liters per metric ton (l/mt) of rock. The mean shale-oil estimate for all samples is 32.9 l/mt (about 7.9 gallons of oil per short ton of rock). Although this yield is too low for commercial development, five of the 27 samples had estimated yields of 60 or more liters per metric ton of rock which would be of economic interest.

Conclusions

The Tripoli formation of Messinian age occupies a large part of the Sicily (Caltanissetta) basin in south-central Sicily. However, the tripolitic rocks do not underlie the entire basin, but they are locally absent owing to nondeposition or to erosion. The thickness of the formation ranges from a featheredge to a maximum of about 45 meters in the vicinity of Barrafranca near the center of the basin where tripolitic rocks make up as much as 25 m of the total thickness of the formation. The formation crops out in many localities in the basin, but the exposures are generally poor, and the kerogen content is much altered, presumably owing to weathering and bacterial degradation of the organic matter. In places, the formation may be as deep as 900 meters. At some localities, the strata are folded and faulted; at other localities, deformation is slight and dips are gentle to moderate.

The Tripoli formation was deposited during Messinian (Late Tertiary) time in a partly restricted marine basin when evaporative conditions were beginning to develop in the basin. Algae and bacteria are the likely precursors for the preserved organic matter in the formation. Rock-Eval data indicate a thermally immature kerogen (Tmax temperatures of 320-400° C) having a high H/C ratio and a relatively low O/C ratio comparable to that reported for kerogen of the Green River Formation of western United States. Shale-oil determinations of the tripolitic rocks are sparse, however, shale-oil yields estimated from Rock-Eval data (Table 1) range from 8 to 125 l/mt. Some of the higher values are of economic interest.

According to Monnier (1978, fig. 3), the thickest development of the Tripoli formation is apparently in an area extending from Piazza Armerina near Barrafranca southwestward 90 km to the vicinity of Canicatti. However, recent drilling by EMS suggests that the Tripoli formation reaches thicknesses of 90 or more meters near Villarosa. Although the available data on the Tripoli formation do not suggest a major oil-shale resource, the data are still too sparse to evaluate the shale-oil potential of these rocks. Additional exploratory drilling with an adequate number of samples analyzed for shale oil are needed.

Recommendations

A modest drilling program of several core holes could provide a good deal of information about the shale-oil potential of the Tripoli formation. Samples could be initially analyzed by an inexpensive method, such as "pyrolysis fluorescence" (PF) analysis that was developed by Shell Oil Company as a rapid method for analyzing large numbers of rotary drill cuttings for petroleum potential. This method, which utilizes a small ultraviolet fluorometer, is relatively simple and inexpensive. Only a gram of material is needed for analysis. The PF results can be calibrated against a suite of samples analyzed by conventional Fischer assay or by Rock-Eval analysis. PF analysis could be used to identify sections of higher-grade core which then could be analyzed by Rock-Eval or Fischer assay.

Areas recommended for exploratory drilling include the oil-shale mine near Serradifalco and the area of thickest development of the tripolitic facies between Piazza Armerina and Canicatti. The exact locations of drill holes should be chosen with the help of EMS geologists. The number of core holes would depend on available funds, however, 4 to 6 holes drilled to depths of about 200-250 meters would provide much informtion about the deposit. Core diameter is not critical; a typical size for oil-shale exploration is NX (core of about 6 cm in diameter). A wire-line core barrel is recommended for best core recovery.

The lithology of the cores should be described by a geologist familiar with oil shale. Gamma ray and density logs of the bore holes would be useful for stratigraphic correlations. PF analyses should be made on samples prepared from 25- to 50-centimeter lengths of a one-quarter split of the core. If the cost of sample preparation appears to be to high, or if the core appears to be low-grade, a preliminary set of samples could be obtained for analysis by drilling small holes every 25 to 50 centimeters or so into the side of the core with a small electric drill and collecting the powder for PF analysis. Polished specimens should also be examined by microscope under UV reflected light.

To maximize the information gained by the exploratory drilling, geohydrologic data should be obtained from each bore hole. The possibility of encountering deposits of sulfur and potash should be considered when drilling. Selected samples should be analyzed for other economic minerals, including uranium.

Some aspects of oil-shale operations in Sicily that might be of environmental concern are (a) mining methods and problems of blowing dust and disposal of spent shale from the retort, (b) water requirements for an oil-shale industry, and (c) problems of air and water pollution. These questions of evironmental concern would need to be addressed if further exploration reveals the presence of an oil-shale resource of potential commercial size and grade. The best shale-oil recovery process will depend upon these concerns as well as the geology of the deposit. In view of the limited supplies of process water, and potential problems of air and groundwater pollution, an *in situ* process may be best.

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Table 1.--Shale-oil estimates for 27 samples calculated from Rock-Eval data and fig. 15

Sample No.	S1+S2 (mg/g)	Shale oil equivalent (l/mt)	Rock type and locality
Samples analyzed by Monnier (1978, table 10)			
773	0.69	7.9	Brown shale, outcrop, Campofranco
775	9.53	17.1	Borehole 2, Giumentaro
776	12.01	19.6	Borehole 4, Giumentaro
779	64.06	73.2	Giumentaro mine
7742	3.25	10.6	Outcrop, Campofranco
77109	23.12	31.0	Zimbalio mine
77117	7.35	14.8	Brown shale, outcrop, Mt. Gallitano
77119	2.4	9.7	Limestone, outcrop, Mt. Gallitano
77126	62.17	71.3	Brown shale, outcrop, Mt. Gallitano
77128	0.38	7.6	Brown shale, outcrop, Mt. Gallitano
77164	12.00	19.6	Gessolungo mine
7713	114.0	124.7	Giumentaro mine
77165	2.37	9.7	Sandstone, quarry, Cozzo Disi mine
77168	9.15	16.7	Tripol. marl, quarry, Cozzo Disi mine
77170	38.94	47.3	Tripol. dolo, quarry, Cozzo Disi mine
77172	47.99	56.7	Dolomite, quarry, Cozzo Disi mine
7656	32.50	40.7	Brown clay, outcrop, Alimena
Samples analyzed by Palmer and Zumberge (1984, table 4)			
E-4	0.60	7.8	Anhydrite, Cozzo Disi mine
E-8	53.4	62.2	Petrol. marl, Cozzo Disi mine
E-13	0.65	7.9	Petrol. marl, near Giummarraro mine
E-16	29.6	37.7	Petrol. marl, outcrop, Agira
E-17	28.6	36.7	Gypsif. marl, outcrop, Agira
E-18	72.6	82.0	Dolo. marl, outcrop, Agira
E-19	9.68	17.2	Shaly marl, outcrop, Santa Nicola
E-20	9.92	17.4	Conglom. marl, stream cut, Alimena
Samples analyzed by U.S. Geological Survey			
3	14.2	21.8	Tripol. marl, quarry, Cozzo Disi mine
3A	13.1	20.7	Tripol. marl, quarry, Cozzo Disi mine

Samples E-8 and E-16 through E-18 are probably from the Tripoli formation. Although the estimated oil yields in the above table are not representative of the Tripoli formation, they do suggest that, at least locally, the shale-oil content approaches that of potentially commercial oil shales.

Figure 1.--Outcrop of white-weathering tripolitic marlstone in the vicinity of the oil-shale mine near Serradifalco, Sicily. Two units in this ledge were mined; a lower unit about 40-60 cm thick and the upper unit about 1 m thick. About 0.5 m of barren rock separates the two units. The grade of the mined units is unknown.

Figure 2.--One of several stairway adits to the Serradifalco oil-shale mine. Although trash filled part of the adit, it may be possible to re-enter the mine through one of these adits for sampling.

Figure 3.--Ruins of the stone foundation for the retort at the Serradifalco oil-shale mine. The large stone building in the center background is a farm building. The retorted oil was sent elsewhere for refining.

Figure 4.--Ruins of the retort building at the Serradifalco oil-shale mine. Judging from the small size of nearby piles of retorted shale, the volume of rock that was mined was small.

Figure 5.--Map showing the areal distribution of the Tripoli formation in the Sicily evaporite basin (adapted from Broquet and others, 1984, fig. 1).

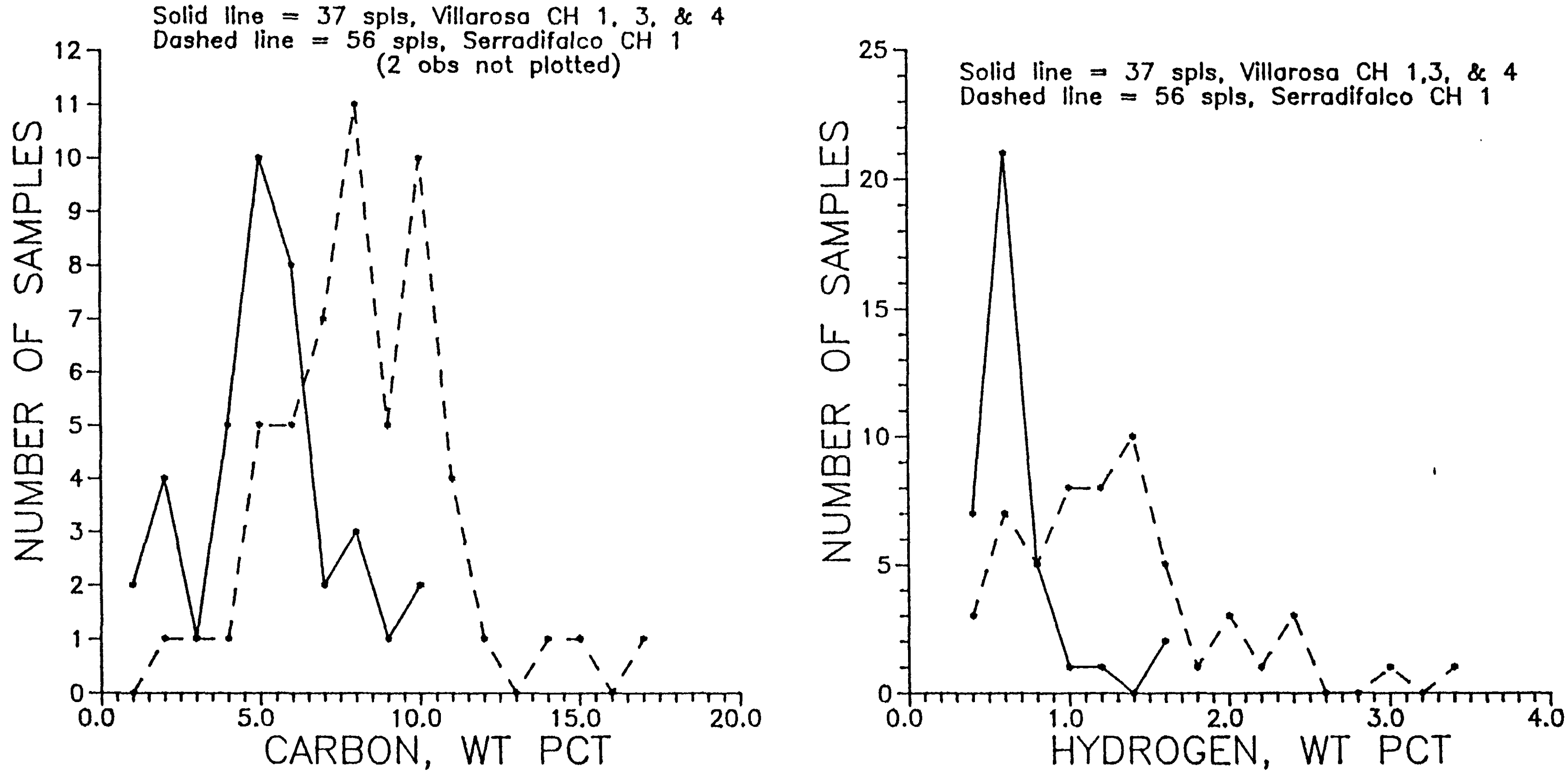

Figure 6.--Frequency distributions of total carbon and hydrogen in core samples of tripoli and associated rocks from Villarosa and Serradifalco, Sicily. Data from Maggiore (1987?).

SICILY BASIN

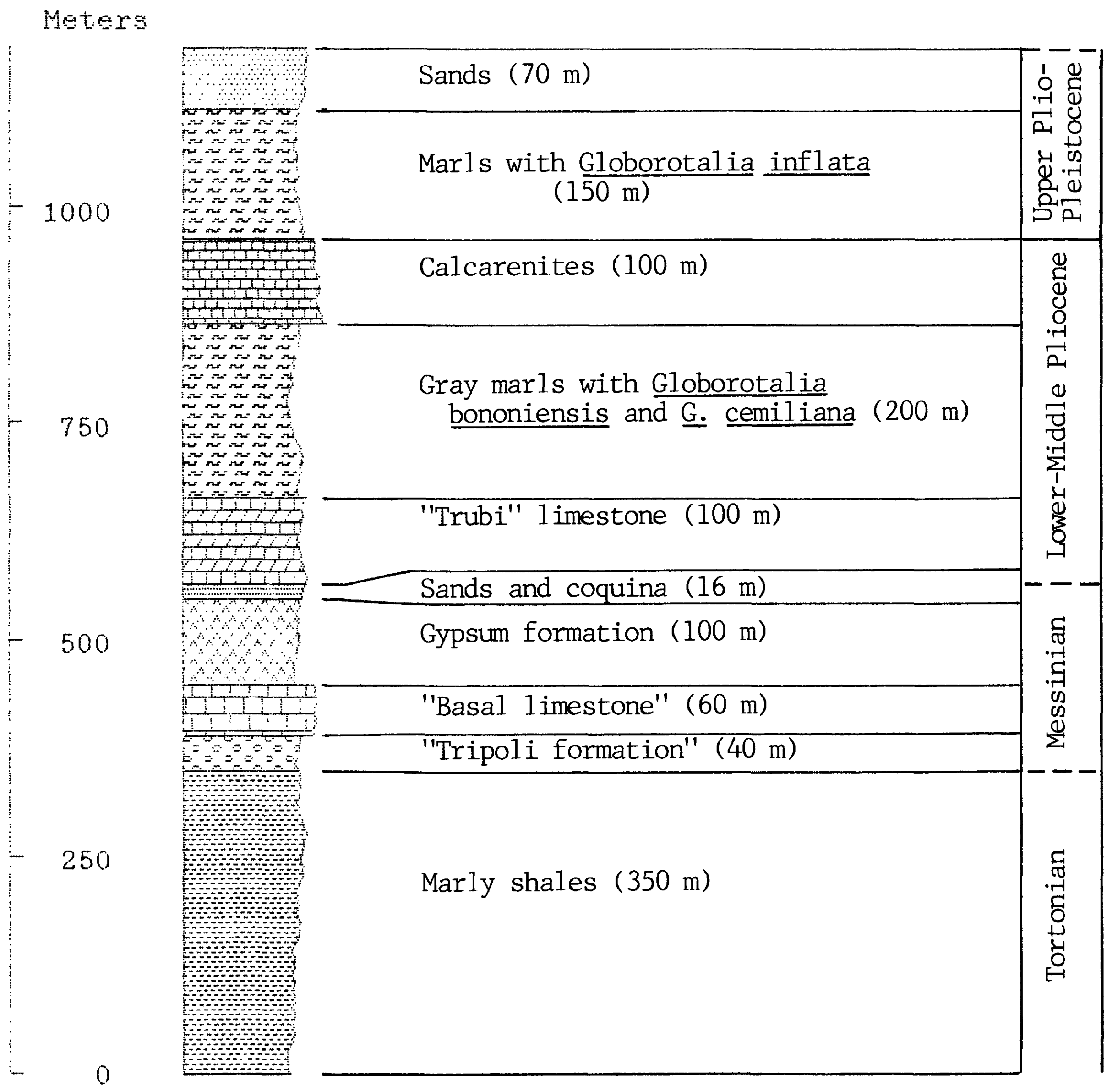

Figure 7.--Generalized stratigraphic section of Tortonian and younger rocks of the Sicily basin (after Ogniben, 1975, fig. 16).

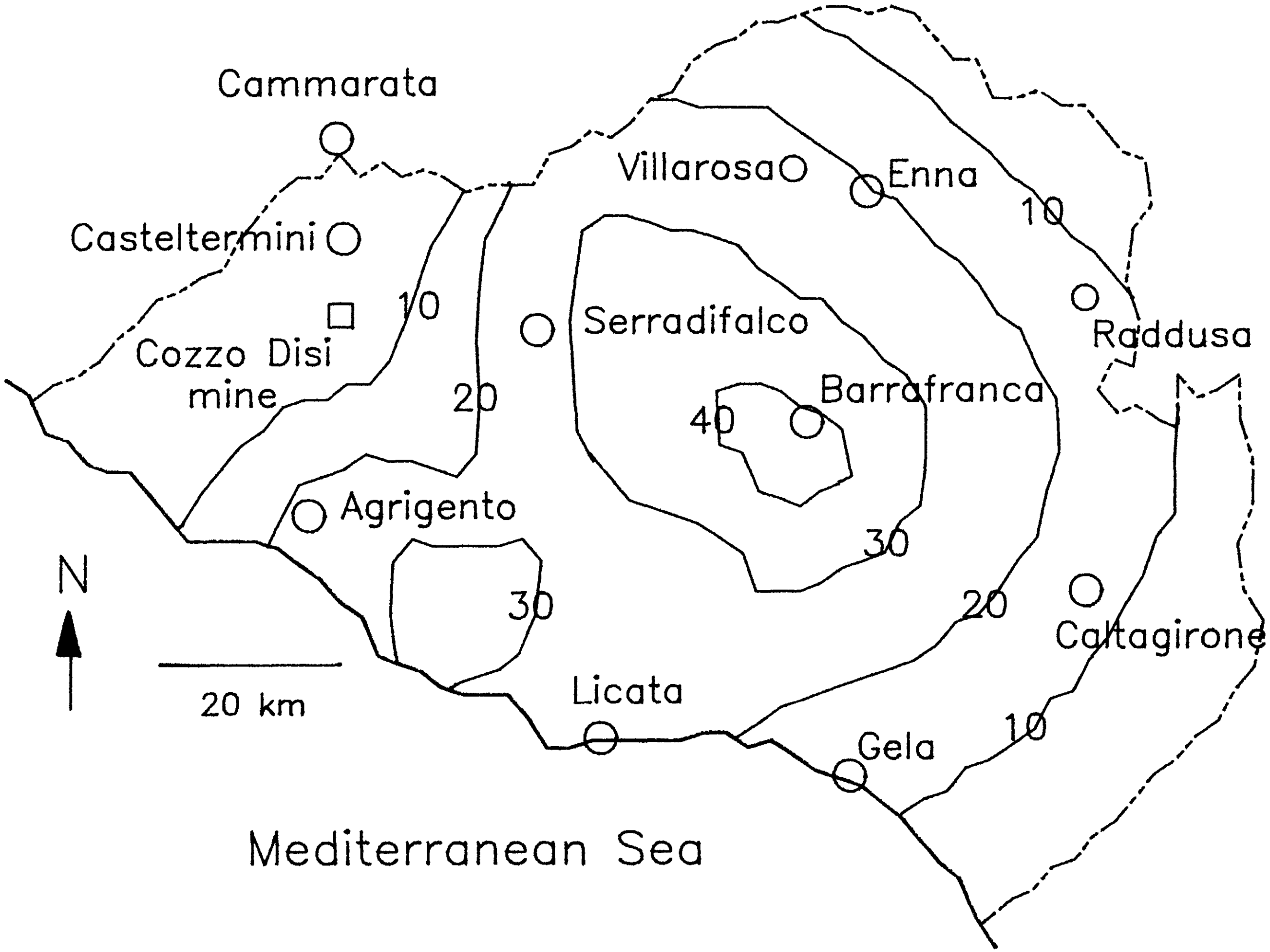

Figure 8.--Isopach map of the Tripoli formation in the Sicily evaporite basin (adapted from Broquet and others, 1984, fig. 7). Contour interval is 10 m.

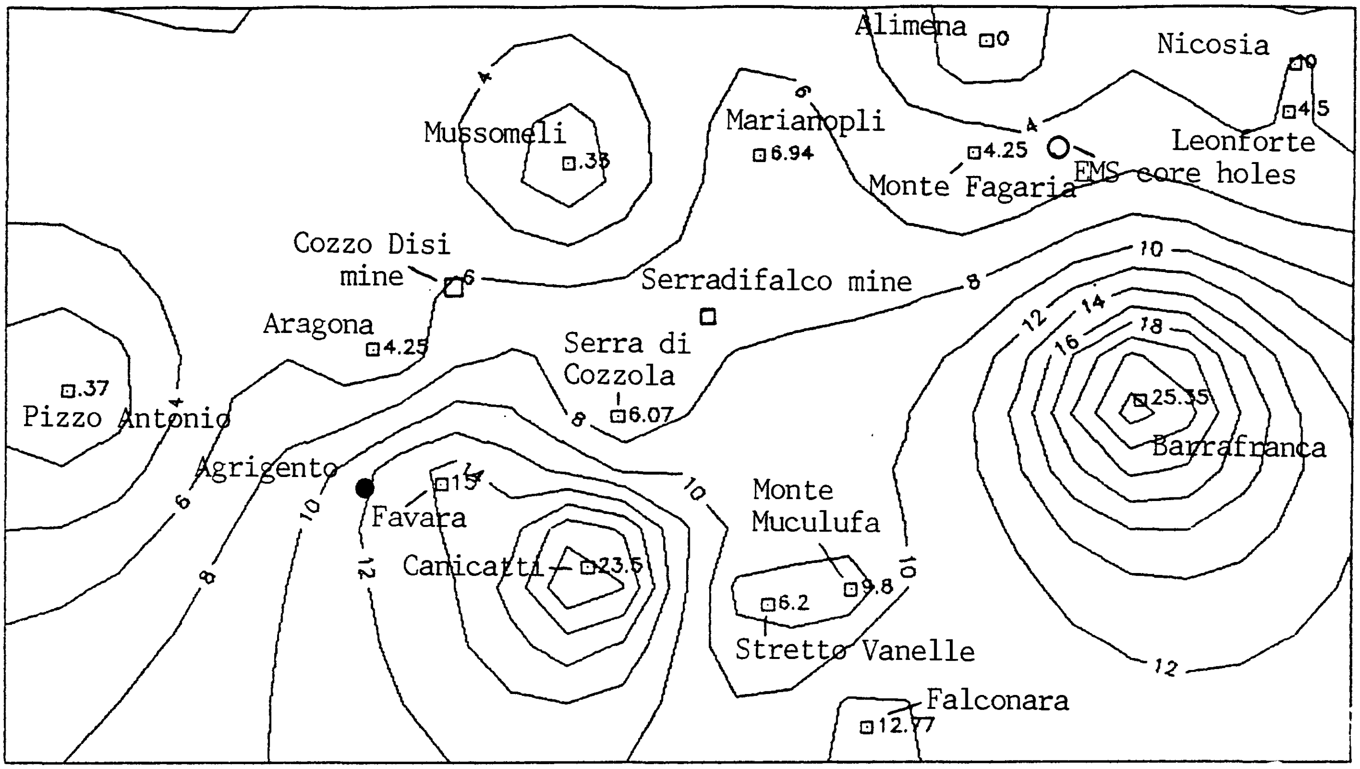

Figure 9.--Isopach map showing the composite thickness, in meters, of only the tripolitic rocks of the Tripoli formation in the Sicily evaporite basin based on sections measured by Monnier (1978).

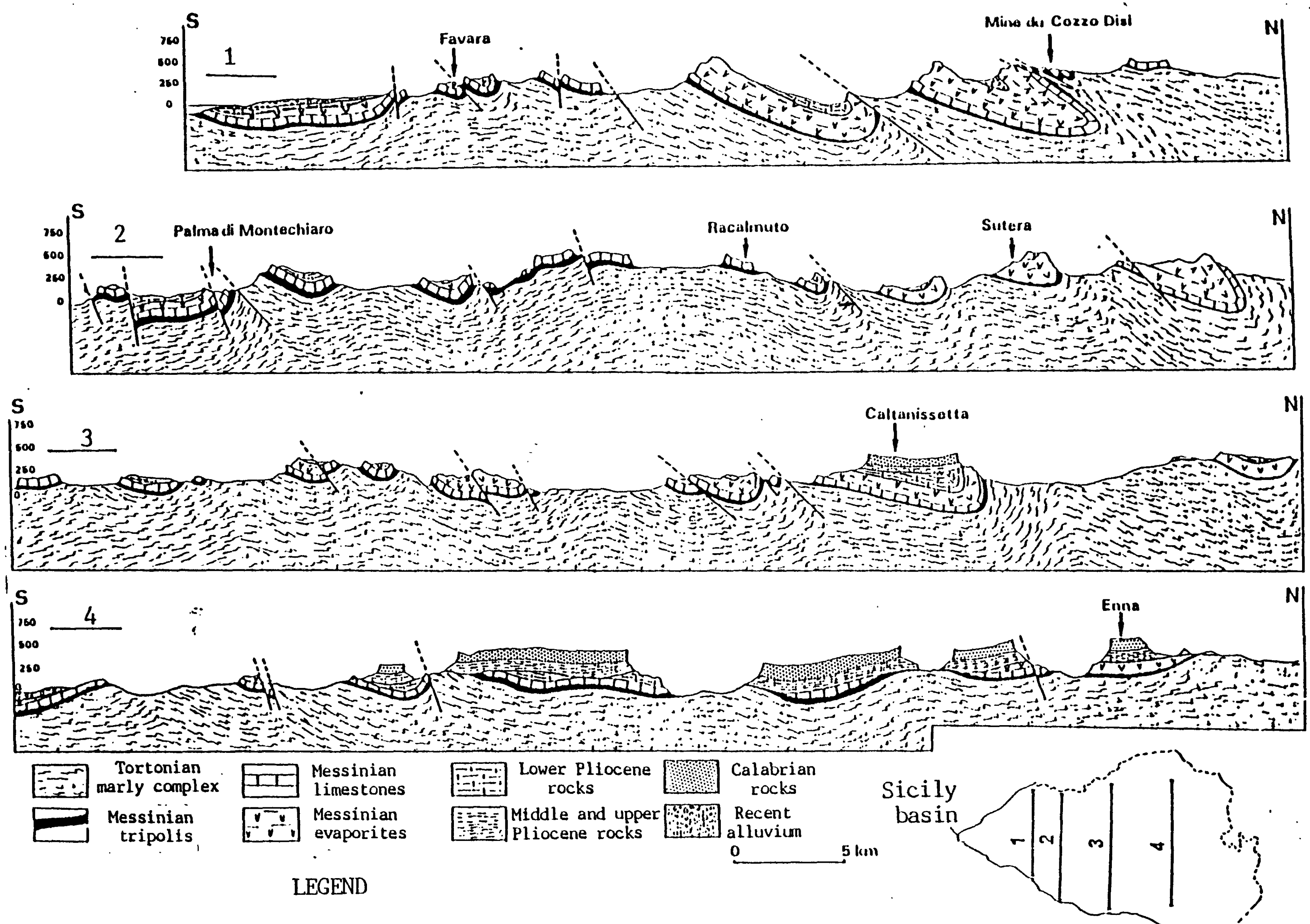

Figure 10.--Structural cross sections of the Sicily basin (from Monnier, 1978, fig.17)

Figure 11.--Folded beds of the Tripoli formation in an open pit at the Cozzo Disi sulfur mine near Casteltermini. Two samples of tripolitic marlstone were collected at this locality for Rock-Eval analysis.

Figure 12.--Gently dipping tripolitic marlstone exposed along a roadcut about 8 km west of Villarosa. Several samples were collected in a sequence between the base of the exposure and a point about 15 m above.

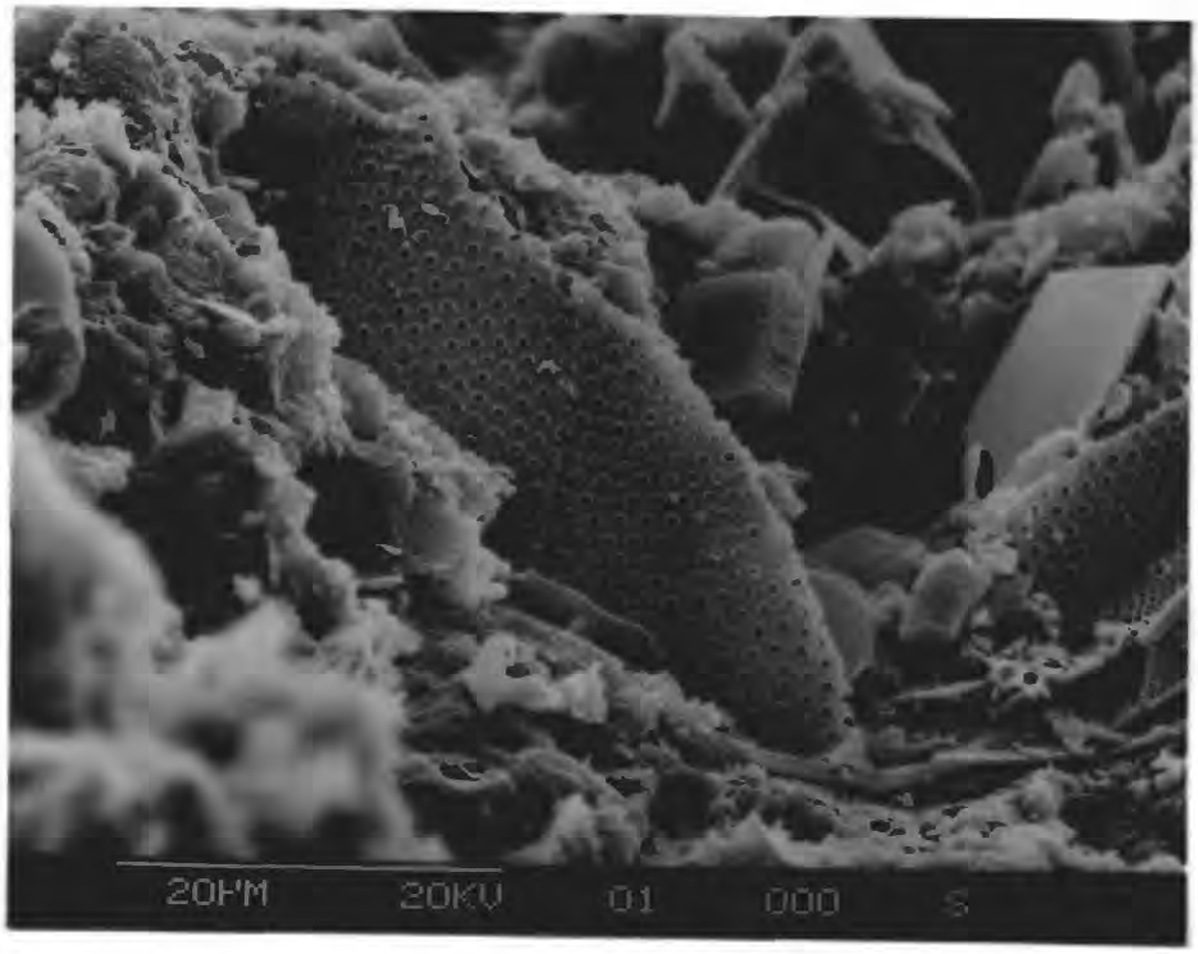

Figure 13.--SEM photograph of tripolitic marlstone from the Cozzo Disi sulfur mine near Casteltermini. Perforate fragments of diatoms and other fossil fragments are abundant. Scale bar is 20 micrometers long.

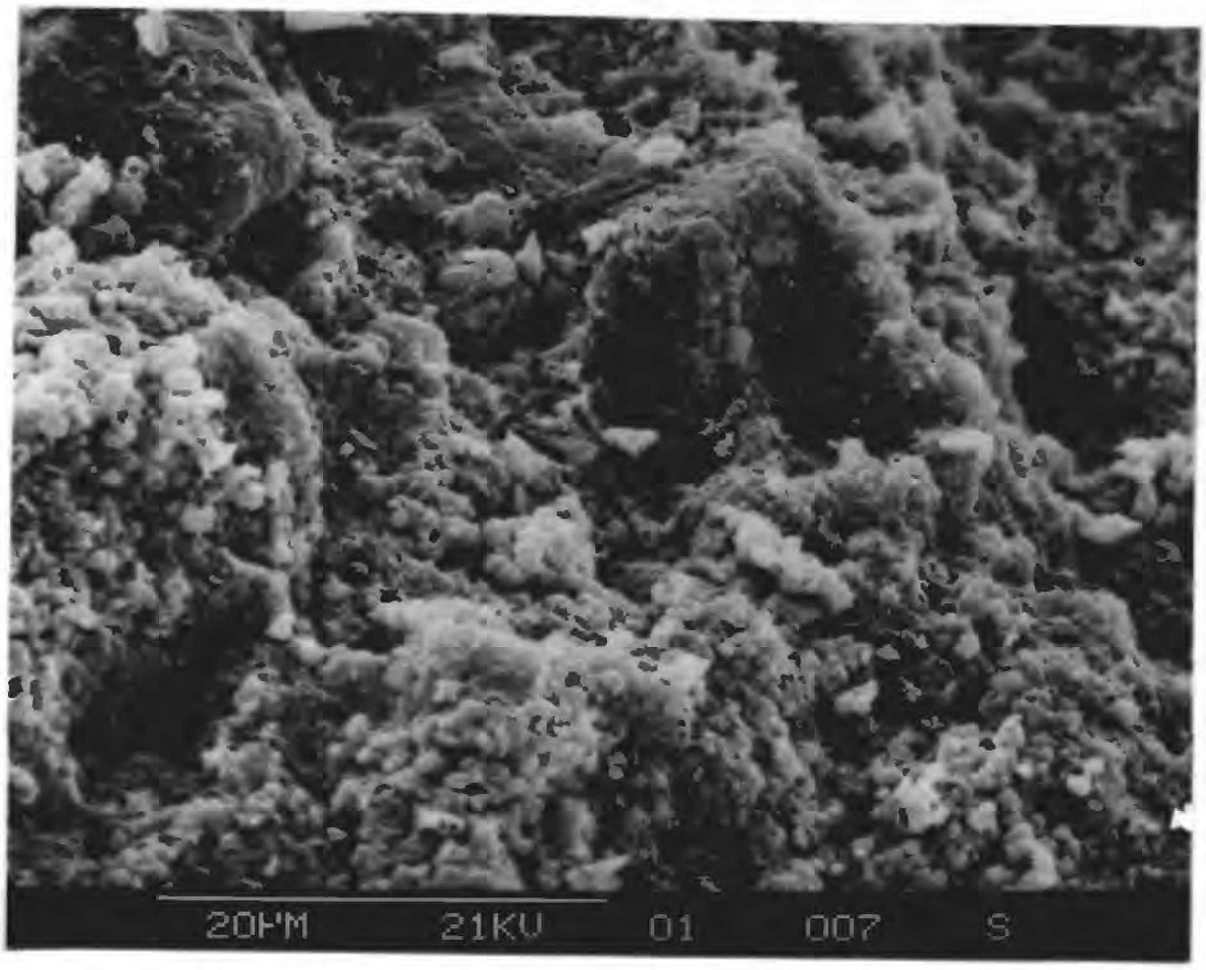

Figure 14.--SEM photograph of a microgranular surface of tripolitic marlstone from the Cozzo Disi sulfur mine near Casteltermini. The minerals identified by X-ray diffraction include abundant quartz, dolomite, calcite, and smaller amounts of tentatively identified kaolinite, illite, and pyrite. Scale bar is 20 micrometers long.

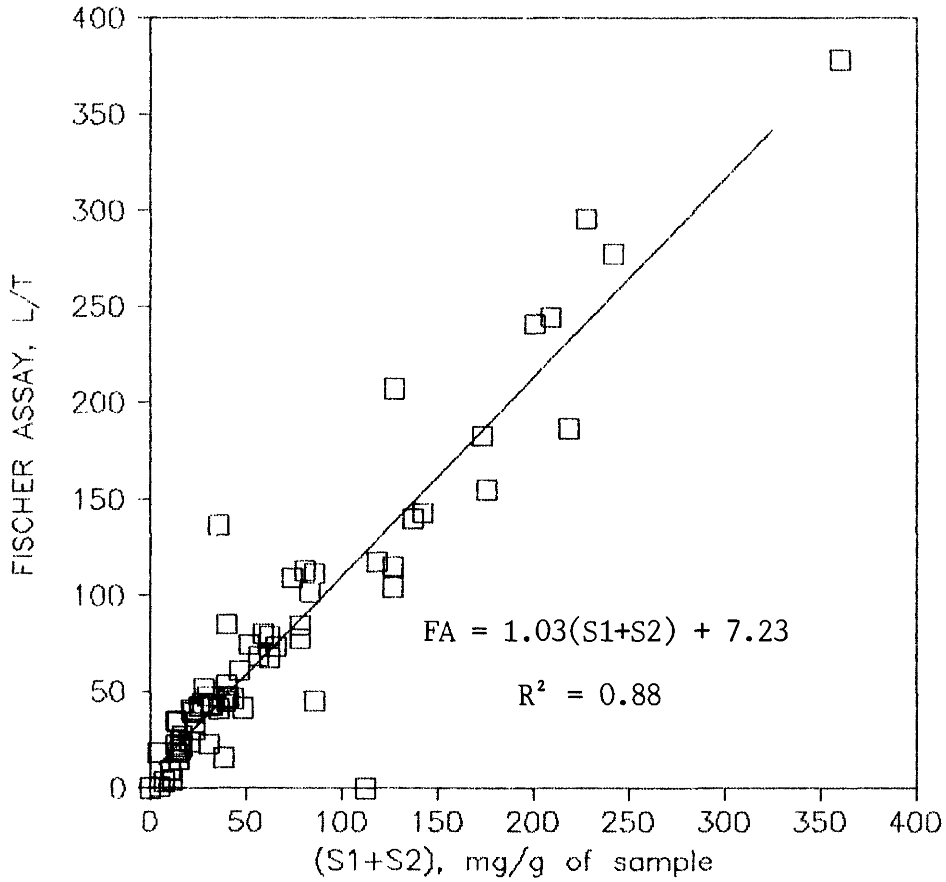

Figure 15.--Shale oil determined by Fischer assay plotted against the sum of the S1 and S2 values from Rock-Eval analyses for 69 samples of oil shale from deposits of different ages and geologic settings from around the world (author's unpublished data).