Chapter 38

FORENSIC USE OF HEAVY MINERALS IN CIVIL AND CRIMINAL INVESTIGATIONS

WAYNE C. ISPHORDING

Department of Earth Sciences, University of South Alabama, Mobile, AL 36688, USA

ABSTRACT

Extensive historic use has been made of heavy minerals in sedimentological and stratigraphic studies. More recently, heavy minerals have been utilised in a wide variety of forensic applications. Five examples are presented to show how heavy minerals have been used in a murder investigation, identify the source of groundwater contamination, quantify the volume of sediment deposited in a wetland area as a result of improper erosion control in an adjacent subdivision, identify the source and cause of the premature aircraft engine failure and in a case involving industrial sabotage. These examples illustrate well how a mineral component, which often comprises less than 1% of a typical sample, can provide the geoscientist with information that is critical in a wide variety of forensic investigations.

Keywords: forensic; sabotage; groundwater contamination

1. PRE-TRIAL RESPONSIBILITIES AND CONSIDERATIONS OF AN EXPERT WITNESS

Webster's Dictionary (Guralnik and Friend, 1964, p. 566) defines forensics as "characteristic of, or suitable for a law court or public debate". While none would argue the economic value of heavy minerals or their use in stratigraphic and sedimentological investigations, only a sparse literature exists documenting heavy mineral use in various forms of litigation. This is unfortunate because a sample's heavy mineral signature can be quite diagnostic and can be employed in a wide variety of applications. To do so effectively, however, the geoscientist must not only be knowledgeable of variations in both local and regional stratigraphic units, and the provenance of these units, but also be familiar with basic legal procedures. For example, it must be kept in mind that under current rules of discovery the scientist does not simply present

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evidence to a jury. Prior to any opportunity of doing so the opposing side will certainly insist on deposing the expert witness. At this time they will have the opportunity of reviewing the witnesses' credentials and may well use any apparent lack of the same to later challenge the admission of a witnesses' report(s) or to prevent actual testimony in court. It is therefore critical during the deposition process for the witness to clearly demonstrate not only qualifications, but also that the "science" being used has precedent, or is widely accepted by the scientific community in his/her field. With respect to the former, potential witnesses who consider themselves "qualified" may find their testimony ruled in-admissible because they lack either: (1) demonstrable experience of employment wherein the particular skill area has been used in the preparation of reports for a client, (2) prior court testimony as an acknowledged expert witness on a subject, (3) refereed publications or presentations at meetings of professional societies that treat the subject, (4) education substantiated from a college transcript or (5) evidence of having taught a particular subject.

The present author knows of several instances where academicians and individuals associated with consulting firms were prevented from testifying simply because they could not produce such evidence. Because of the breadth of material covered under the subject of geology, the mere possession of an advanced degree in the field does not necessarily qualify one as an expert in all areas. In a recent case, for example, an expert witness (a metamorphic petrologist) offered by the opposing side as an expert "mineralogist" was ruled unqualified to offer testimony. Heavy mineral evidence was critical in connecting a defendant with a specific contamination problem. It was quickly shown that: (1) the defendant's expert had no knowledge of the mineralogy of local and regional clastic sedimentary units, (2) had never carried out a single heavy mineral analysis, (3) had no publications on the general subject of heavy mineral interpretation and (4) had never even visited the area. In another instance, a potential witness whose expertise was in clay mineralogy was disqualified because, even though he had taught sedimentary petrology for several years, he was forced to admit that he was unfamiliar with the local geology, had never performed a heavy mineral analysis and did not include such instruction in his course, was not knowledgeable about procedures applicable to the sampling of unconsolidated clastic sedimentary units and had no knowledge regarding constraints imposed by the use of parametric versus non-parametric statistical methods for analysis of heavy mineral data. For individuals to represent themselves to a client as "experts" when they lack such qualifications is not only a disservice to the client, but also a glaring violation of basic ethics in our profession! Unfortunately, our field is not exempt from such instances.

As noted above, it is not solely an expert witness' credentials that may be attacked by the opposing side, but also the scientific basis for any reports or testimony that is to be offered. It is therefore incumbent on the witness to provide a basis for such testimony. This may be in the form of reference(s) to prior cases where the specific type of evidence was accepted by the court, or by citation of refereed articles in scientific journals considered creditable by the scientific community. An abundant literature, for example, can be cited to document the use of heavy minerals for stratigraphic analysis and correlation (Rosen, 1969; Isphording, 1976; Isphording and Flowers, 1980; Isphording et al., 1984; Morton et al., 2007: this volume), identification of depositional environments (Suzuki, 1975; Lee et al., 1988; Nechaev, 1991), provenance investigations (Van Andel and Poole, 1960; Isphording, 1971; Isphording and Flowers, 1983; Morton, 1985; Smale and Horton, 1987; Morton et al., 1992), tectonic settings (Nechaev and Isphording, 1993) and as palaeoclimate indicators (Isphording, 1970; Schneiderman, 1997; Egger et al., 2002). Other applications are also described in Mange and Maurer (1992).

While use of such references is not generally made during the trial phase of litigation, the ability to cite and to produce such references will be demanded by the opposing side at the time of deposition. Consequently, a witness whose deposition is to be taken is generally served with a subpoena duces tecum. The subpoena will not only include the time and place where the deposition is to be taken but also demand, but not be limited to, the following:

1. the deponent's current curriculum vitae;
2. a list of all cases in which the deponent has been tendered as an expert in the last 5 years;
3. all documents provided to the deponent by his client (i.e. attorney) or those represented by the attorney(s);
4. the deponent's entire case file, including, but not limited to, all correspondence, notes, field notes, raw data, records, computations, digital images, audio and/or video tapes;
5. *all documents, texts, journals, articles, publications etc., deponent reviewed or relies upon as authoritative, which were used in formulating his opinions in this matter* (author's italics).

Because a judge is not present at the time a deposition is taken, the witness has somewhat more freedom to elaborate and render opinions in order to convince the opposing legal team of not only his/her expertise, but also the significance and interpretation of the results of any studies that were carried out. This freedom may not be present during actual trial when opposing attorneys can demand simple "yes–no" answers to questions that have been prepared to limit testimony that they consider damaging to their client. Thus, the deposition takes on even greater significance because the opinions and reports rendered by the expert may well convince the opposing attorneys that their case either is unwinnable or might result in a significant damage award against their client at the time of trial and that a pre-trial settlement is the best course of action.

One final word of caution and advice is offered by the author, based on ~40 years of work as an expert witness. In all but the most exceptional instances the expert witness should never be apprised of the "case facts" by either a plaintiff or defendant, prior to being contacted by an attorney (and retained by the attorney). During deposition (and trial) the witness will be invariably asked when contact about the case was first made, and *who* made the contact. It is critical to be able to answer that the witness was first contacted by the attorney and asked to carry out an investigation to obtain case facts. As such, the perception of an unbiased scientist is maintained and any work produced has been, therefore, objectively generated by the scientist who will serve as an "expert witness" on the matter. If the report is prepared at the request of the plaintiff (or defendant), the jury will often perceive the expert witness as an "advocate" for the client and that any report has been "cleansed" of any damaging information. The distinction is critically important at the time of trial.

2. PRESENTATION OF HEAVY MINERAL EVIDENCE IN COURT: JURY INSTRUCTION

To use heavy minerals at the trial stage of litigation it is necessary to first "educate" the jury as to what heavy minerals are and what they represent. Years of experience has shown that the easiest way of showing "what" they are, can be most easily accomplished by first telling the jury that sediments are simply the weathered debris remaining from erosion of rocks in upland areas. They are told that most of the sediment consists of the mineral quartz (a specimen of beach sand is helpful at this point) and that heavy minerals are always a minor fraction of the sediment (usually less than 1%). The debris is then carried by rivers and streams and may be deposited on the flood plain of rivers, during time of high water, or may be carried all the way to the ocean where it forms beaches. Then, using a magnet covered by a white piece of paper, the magnet is passed over a sand sample containing magnetite. The magnetite is readily apparent to the jury adhering to the paper. It is then pointed out that magnetite is only one of a number of heavy minerals and that, in fact, any mineral that has a specific gravity greater than quartz (technically, greater than 2.85) is considered as a heavy mineral. The same sample can then be used to show the jury that the magnetite will sink in a heavy liquid, such as bromoform or tetrabromoethane, while the quartz will "float". The jury is then advised that each mineral can be identified by its specific optical properties and that strata deposited during a restricted time period within the same general area will all contain approximately the same relative percentages of various heavy minerals. It is also pointed out that if there is a significant "time gap" in the depositional process, erosion will likely have exposed older rocks and that these may well provide either some different heavy minerals or, at the very least, different percentages of mineral species than were formerly seen. It can then be emphasised that the relative percentages of the various heavy mineral species can thus serve as a "fingerprint" for various stratigraphic units and that these percentages do not vary greatly within a given area.

3. EXAMPLES FROM CASE HISTORIES

3.1. Michael Macdonald Murder Case

This case received nation-wide publication in the United States by virtue of the fact that it was one of the last in the country to involve the notorious Ku Klux Clan.

On March 21, 1981 a young, black, 19-year-old male was abducted from a street in downtown Mobile, Alabama, and taken across Mobile Bay to a site where he was brutally murdered. The crime was in apparent revenge for a mistrial granted in a case involving the murder of a white Birmingham, Alabama police officer. Two members of the Ku Klux Clan were arrested and a third was subsequently arrested and charged as an accessory. Ultimately, one of the defendants was executed for the crime and the other two are now serving life sentences. Evidence gathered and presented by the prosecution, however, was nearly compromised by the lack of expertise of the prosecution's expert on chemistry. Inappropriate statistical tests were used in an attempt to associate the defendant with the victim at the crime scene, and mineralogical evidence that could have been used to accomplish this was not presented. Fortunately, for the sake of justice, two of the defendants opted to plea bargain and implicated the third as the actual murderer, in exchange for life sentences.

All defendants were clearly guilty, however, and each had been present at the crime scene. Mineralogical evidence was present on the soil in the truck, on the defendant's clothes and shoes and on the victim that categorically proved this. The defendants had stated (prior to the plea bargain) that they were "innocent" and had spent the evening the murder took place at the principal defendant's home and had not ventured elsewhere in the City of Mobile. Fig. 1 shows a geological map of the south Alabama area and it is seen that the defendant's home is located in an area of Mobile adjacent to Mobile Bay that is underlain by Quaternary terrace deposits. The crime, in contrast, was committed across the bay at a site underlain by sediments of the Plio-Pleistocene Citronelle Formation. These stratigraphic units are distinctively different in their mineralogy (see Isphording, 2004a) and can be differentiated by clay mineral analysis and heavy mineral content. The floodplain deposits contain both smectite clay and calcite (as fine grained shell material) whereas the Citronelle sediments are devoid of both of these minerals. The heavy mineral suite is similarly different (see Table 1). The terrace deposits are consistently lower in ilmenite, zircon and kyanite and higher in leucoxene and staurolite. Further, the terrace deposits invariably contain small percentages of the less resistant heavy minerals

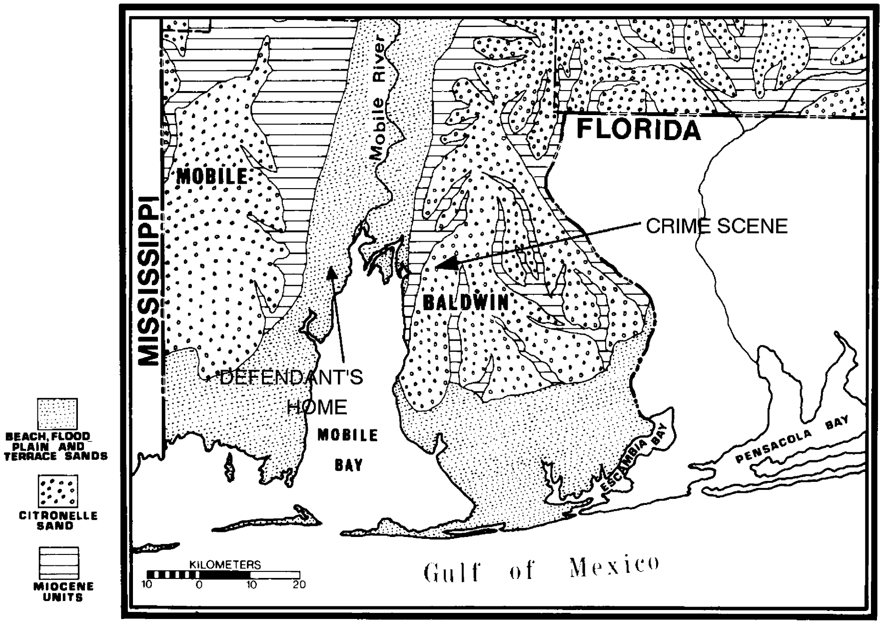

Fig. 1. Location map showing principal geological units exposed in Mobile and Baldwin counties with crime scene and defendant's homes noted.

Table 1. Heavy mineral content of Citronelle, Miocene and Terrace deposits and their ZTR index

	Citronelle Fm. (Crime scene)			Miocene sediments			Terrace deposits		
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
Black opaques	36	34	30	30	22	30	27	22	21
Leucoxene	6	7	4	12	21	15	13	13	14
Zircon	4	7	4	2	1	1	5	6	7
Tourmaline	6	7	6	13	15	16	8	8	10
Staurolite	14	11	13	14	16	11	16	19	15
Rutile	7	8	10	5	5	4	5	6	7
Kyanite	15	15	14	20	16	19	12	10	8
Garnet	0	0	0	1	Tr	Tr	0	0	Tr
Tan opaques/others*	12	11	19	3	4	4	14	16	18
$\sum$	100	100	100	100	100	100	100	100	100
ZTR index	1.4	1.8	1.0	3.0	3.2	4.3	2.6	2.3	2.4

*Others = sillimanite, andalusite, epidote, sphene, hornblende, pyrite etc., depending on stratigraphic unit.

hornblende and garnet. The [zircon + tourmaline + rutile (ZTR)] index is also clearly different. Soil samples from the defendant's automobile, shoes and clothes possessed a typical Citronelle mineralogy, as did samples collected from the victim. This information also could have been presented to the jury as evidence that the defendants had lied and had, at the very least, been to some site underlain by the Citronelle Formation.

3.2. Alabama State Docks Industrial Vandalism Case

In 1978 the author was contacted by an official at the State Docks and asked to assist in a legal matter. A large Caterpillar bulldozer, model D-9, had been vandalised and its engine destroyed by someone who had placed sand in the engine's crankcase. The replacement value of the engine was nearly US$ 100,000. The situation was such, however, that the bulldozer was owned not by the State of Alabama, but rather by a private contractor. Further, though the State Docks acknowledged that it was responsible for the equipment's security, the insurance carrier demanded proof that the sand had been introduced while the bulldozer was on State property (the owner had admitted that the unit had been used the previous week at a quarry in northern Mobile County).

The contents of the crankcase were examined by first removing all organic material by treatment with methyl ethyl ketone and, subsequently, hydrogen peroxide. All metal fragments were removed by passing a strong magnet over the remaining sample. Several samples were also obtained from the quarry in northern Mobile County where sand and gravel from Miocene age sediments were being mined and from indigenous sediments at the State Docks site. All samples were then sieved on a one-phi interval to obtain the size frequency distributions and to obtain size fractions for heavy mineral separations. Tetrabromoethane (density 2.96) was then used to carry out heavy mineral (and light mineral) separations on the 1.0–2.0 phi fraction (250–500 μm), the 2.0–3.0 phi fraction (125–250 μm) and the 3.0–4.0 phi fraction (62.5–125 μm), and the mineralogy of each fraction determined by standard petrographic examination. The results of these analyses are shown in Table 2.

Examination of the data in Table 2 would likely lead an experienced geologist to conclude, on the basis of the size analysis alone, that the material found in the bulldozer's crankcase was indigenous material from the State Docks facility. This is strongly indicated by the paucity of granule size [particles > -2 phi, (4mm) in size], the lower percentages of particles in the very fine sand category (3.0–4.0 phi) and higher quantities of sediment in the <4.5 phi (44 μm) size category. An argument could be raised, however, that a comparison of the size of particles would not be

Table 2. Mineralogical and particle size analyses for samples from State Docks, quarry site, and bulldozer crankcase

	Alabama State Docks		Quarry samples		Bulldozer sample
	Sample 1	Sample 2	Sample 1	Sample 2	
Size analysis (%)					
Phi value					
−2.0 to −1.0	0	0.7	2.41	2.13	0
−1.0 to 0.0	0.55	1.04	1.55	1.63	0.64
0.0 to 1.0	3.08	2.56	2.14	1.66	2.88
1.0 to 2.0	9.58	11.31	7.44	8.32	8.57
2.0 to 3.0	21.82	20.64	16.07	18.28	22.72
3.0 to 4.0	36.06	39.52	47.08	43.97	38.50
4.0 to 4.5	17.04	13.11	18.55	21.78	16.62
< 4.5	11.87	11.12	4.76	2.23	10.07
	100	100	100	100	100
Mineral analysis (%)					
Muscovite	0.2	Tr	0	0	0
Feldspar	Tr	0.4	0	0	Tr
Garnet	0.4	0.2	0	Tr	0.1
Epidote	0.6	0.2	0	0	0.2
Hornblende	0.5	0.2	0	0	0.3
Kyanite	19.7	23.3	15.3	16.4	17.9
Rutile	7.0	6.4	2.3	6.6	7.7
Sillimanite	0.5	0.3	1.0	0.7	0.3
Staurolite	17.9	20.6	9.9	13.3	20.8
Tourmaline	8.5	9.4	16.5	15.8	10.1
Zircon	2.7	3.1	9.5	6.2	1.9
Ilmenite	32.2	29.8	19.5	23.6	30.4
Leucoxene	4.6	2.1	12.1	7.7	3.9
Tan opaques	5.1	3.9	11.5	8.0	4.1

Note: Trace amounts of other minerals (andalusite, mica, sphene, spinel, pyrite etc.) were also present in the samples.

valid because of "abrasion" that took place when particles were carried upward in the oil and crushed by the piston rings. Although this point was never raised by the State Docks insurance carrier, it is a valid point and could have obfuscated the result. Not arguable, however, were the results of the mineral analyses. Samples from the sediments at the State Docks were very similar in mineral content to that found in the bulldozer crankcase and patently dissimilar to minerals found in the quarry samples. Epidote, garnet and feldspar are totally lacking in Miocene sediments in the south Alabama area but are common in modern river sediments and beach sands in Alabama. These minerals also occur in the recent sediments that comprise flood plain materials on which the State Docks are located. Hence, presentation of this information by State Docks personnel to the insurance carrier resulted in the State Docks insurance company compensating the contractor for damage to his equipment without any attempt to avoid responsibility for liability.

3.3. Teledyne Continental "Mystery"

The author was involved in a somewhat similar case in 1979 when he was approached by the senior metallurgist of the Teledyne Continental Aircraft Company. This company operates a facility in Mobile, Alabama, building and overhauling commercial aircraft and aircraft engines. A problem had developed in a particular engine model that was being supplied to the Piper Aircraft Company, in California. Piper reported that a number of incidents of compression loss and premature engine failure had been reported by users. Bench testing of the engine by Teledyne engineers, however, did not show any anomalous failure of the engine, and although a number of engines were torn down, following different periods of sustained operating times, all failed to show anything other than expected wear. Hundreds of man-hours were spent on this problem with no results, except that engines returned to the Mobile, Alabama plant did have elevated levels of fine particulate material in the crankcases. In desperation, this material was sent to the author for identification. Again, standard laboratory methodology was used to "clean" the organic component from the sediment and to isolate both the light mineral and heavy mineral fractions. The results of petrographic examination of the light mineral and heavy mineral fraction are shown in Table 3.

Even the most cursory examination of the sample by one familiar with mineralogy would have led to an immediate conclusion that the crankcase material was nonindigenous sediment. The Teledyne facility is located not far from Mobile Bay and lies on terrace sediments deposited during higher stands of the sea during the Pleistocene. While some orthoclase feldspar has been observed in terrace sediments, the presence of plagioclase in the crankcase sample was irrefutable proof that the material was not of a local nature. This was further confirmed by the similar presence of orthopyroxene, clinopyroxene, epidote, apatite and magnetite. With the exception of the very rare occurrence of epidote and apatite, the other minerals are totally lacking in all south Alabama Neogene sediments. The crankcase sample possessed a mineral suite that strongly resembled one associated with volcanic rocks (e.g., andesites).

The Teledyne engineer was advised that the contaminants definitely were *not* introduced during the manufacturing process in Mobile, Alabama. He was asked if

Table 3. Results of mineralogical analysis of particulate material present in aircraft engine crankcase

Mineral	Per cent
Quartz	32.1
Feldspar (Pl + Or)	12.1
Clinopyroxene	2.4
Orthopyroxene	0.6
Amphibole	14.6
Epidote	2.1
Garnet	0.6
Zircon	1.2
Rutile	0.3
Apatite	0.7
Sphene	0.3
Ilmenite/magnetite	32.1

there was any post-manufacturing assembly that was carried out at Piper's California facility and was told that a special oil filter was installed by Piper. A request was then made for Teledyne to obtain a sample of the sediment at the Piper plant. A company jet was used to immediately fly to California, acquire the sample and then return it to Mobile. Examination of the sample showed that the mineral suite was nearly identical to that found in the crankcase sample. The problem was finally traced to failure of a gasket on the oil filter to produce an air-tight seal. Consequently, when the planes were tested in California, dust and other sediments on the runway were being aspirated into the engine. This problem persisted after sale of the aircraft and eventually caused premature failure of the engine.

3.4. *Conoco–Agrico Groundwater Contamination Case*

This case documents a classical example of the use of heavy minerals in forensic investigations. The study was centred in Pensacola, Florida (Fig. 2) and involved the source of contamination of municipal drinking water wells in the Pensacola area.

Unlike most other cities located around the margin of the northern Gulf of Mexico, Pensacola is wholly dependent on deep wells to supply its drinking water. Beginning in the late 1950s, concern began to be raised about the pH and high levels of sulphate and fluorine in some of the wells. Subsequently, in 1959, the first of 16 major wells on which the city was dependent was ordered shut down. The likely source of the contaminants was traced to a massive groundwater plume emanating from a large phosphate manufacturing facility that had been operating at the site since the 1890s. Initially, the plant simply produced sulphuric acid from pyrite. Beginning in the 1920s, however, superphosphate became the main product and was derived from treatment of phosphate ores shipped from peninsular Florida. The plant was sold to Conoco by American Agricultural Chemical Company in 1963 and Conoco continued to produce phosphate until 1972 when the Williams Company purchased the operation and formed the Agrico Division. Agrico manufactured

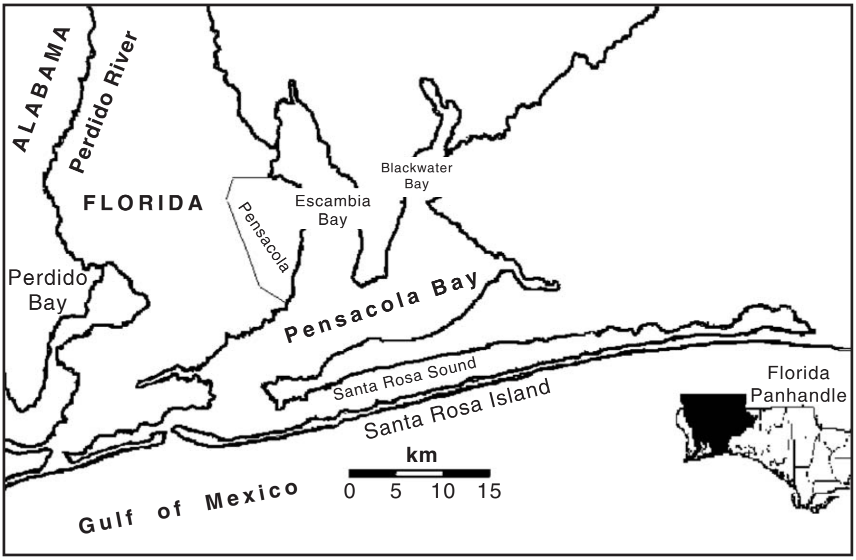

Fig. 2. Pensacola, Florida location map.

superphosphate until 1975, at which time the facility was shut down and the site abandoned. All buildings were removed in 1979. During the 1980s, the Florida Department of Environmental Regulation continued to address concern to the Escambia County Utilities Authority (ECUA) about high levels of a number of contaminants in water wells. In 1987, the facility was declared a Superfund site. In 1992, a second drinking water well was ordered shut down because of low pH and high levels of aluminium, sulphate and fluorine. It was during this time that first mention of high levels of radium (Ra), up to 20.8 picocuries per litre (pCi/l), were first noted in monitoring wells by Conoco personnel but this was not passed on to state or local agencies. In 1996, however, radium was included on the Environmental Protection Agency's (EPA) contaminant list that permits no more than 5 pCi/l in drinking water wells. As a result, one additional well was shut down in 1998 due to high radium and nitrate levels and a fourth well was ordered abandoned in 2000 because of unacceptable radium, nitrate and aluminium levels. Late in 2000, a class action suit was filed against the former owners on behalf of property owners.

The defendants did not strongly contest that the elevated aluminium, sulphate and fluorine, values observed in the groundwater plume, and the low pH, might have originated "in part" from the unlined ponds on the property to which manufacturing effluent had long been pumped. They did strongly contest, however, the allegation that they were similarly responsible for the elevated $^{226+228}$Ra levels that had forced recent closure of two of the wells. They argued that only ^{226}Ra is associated with fertiliser manufacturing and that any ^{228}Ra present must be from "natural sources" and, therefore, not the result of treatment of ores at the site. ^{226}Ra, the defendants argued, is an acknowledged daughter isotope formed by radioactive decay of ^{238}U. Uranium (U) is a ubiquitous substitutional impurity for calcium in phosphate (apatite) ores from around the world. ^{228}Ra is not a daughter isotope in this series and originates only by decay of ^{232}Th (thorium). The source of the ^{228}Ra was thus critical to both sides involved in the litigation and, to a large degree, the major part of any damage award would hinge on the plaintiffs being able to show that this isotope, also, was associated with the manufacture of superphosphate fertiliser.

To anyone familiar with the heavy mineral content of Florida Miocene age sediments, the source of the radium was no mystery. Miocene sediments throughout peninsular Florida are known to possess the mineral monazite as part of the heavy mineral suite (see Pirkle et al., 1965; Lewis, 1978; Garner, 1980; Scholten and Timmermans, 1996; Isphording, 2004b). In fact, the mineral was mined for an extended period of time at a site near Green Cove Springs, Florida. Monazite, chemically, is (Ce,La,Th,Y)PO_4. ^{228}Ra is a daughter isotope of ^{232}Th. The ultimate source of the mineral can be traced to erosion of crystalline rocks in the Piedmont and Blue Ridge Mountains of Georgia, South Carolina and North Carolina. Even though present only in trace quantities in the ores, the amounts that were processed at the site over a period of some 50 years are more than sufficient to explain the levels of ^{228}Ra now seen in groundwater in the down-gradient plume (see Table 4). Unlike the ^{226}Ra isotope derived from uranium in the ores, and which typically remains with the superphosphate after the ore is processed into fertiliser, the ^{228}Ra isotope is largely discharged into the waste stream that was sent to the unlined ponds. Treatment of the ores with sulphuric acid during the manufacture of superphosphate dissolved the monazite and thereby liberated the thorium (and radium).

One final argument raised by the defence that was necessary to address involved their contention that the ^{228}Ra might well have been derived from thorium present in monazite in the Pensacola area indigenous sediments. The author was able to produce over 100 heavy mineral analyses from his own personal files documenting the fact that monazite, other than a few rare grains, is essentially absent as a heavy mineral component in the Miocene sediments and the Plio-Pleistocene Citronelle Formation sediments that crop out in the Pensacola area (see also, Coe, 1979). The mineral is found in trace amounts in recent sediments and in Pleistocene age beach deposits but these units are restricted to the near-coastal zone.

As a result of this testimony, and that by the plaintiff's hydrologists, a pre-trial settlement was reached with the defendants. On April 22, 2004, the Pensacola News

Table 4. Radium activity associated with monazite occurring as a heavy mineral constituent of Florida phosphate deposits

Calculation of radium activity per unit mass of ore
(1) Florida phosphate ores have a heavy mineral content of ~0.17% (Isphording, 2004b). One percent of this is monazite (thus the average monazite content is ~0.002%).
(2) Monazite contains 5% thorium; 87.88% of ThO_2 is thorium.
(3) One pound (0.45 kg) of ore therefore contains: (1 lb)(% heavy mineral in ore)(% monazite in ore)(% ThO_2 in monazite) (% thorium in ThO_2)(100) $= 7.47 \times 10^{-7}$ lb of thorium (3.39×10^{-7} kg of thorium).
(4) The specific activity of ^{232}thorium is 0.0041 disintegrations per second (dps) per microgram and 1 Curie $= 3.7 \times 10^{10}$ dps.
(5) Hence, 7.47×10^{-7} lb of thorium/1 lb ore $\times$ 453.59 g/lb $\times 1.1 \times 10^{9}$ pCi/g $=$ 37.3 pCi/g $=$ the activity of radium in 1 g of ore.

Journal printed a story stating that Conoco had agreed to a US$ 70,000,000 settlement with Pensacola residents whose property was potentially contaminated by the toxic plume that had spread down gradient from the manufacturing site. While still alleging that the plume posed no risk to the residents, Conoco thereby avoided inclusion of an even larger area of the city in the litigation. As such, this settlement amounted to the largest ever reached in a case involving groundwater contamination in the United States.

3.5. Lake Forest Estates: D'Olive Bay Habitat Destruction Case

It is a well-known fact that large-scale urban or industrial development projects may profoundly alter rates of erosion (see Fig. 3). The magnitude of such changes is generally ignored because of a general belief that no reliable means exists that allows the identification in core samples of "pre" versus "post" impact sediments (impact referring to the time at which the accelerated erosion began as a consequence of land clearing and construction activities). The geologist, more and more frequently, is involved in such types of litigation and heavy mineral analysis may often be used to aid in "quantifying" the magnitude of changes that have taken place.

An example illustrating this involved a case where improper erosion controls associated with development of a large subdivision (1500 acres ~625 hectares) caused an extensive amount of sediment to be deposited in an adjacent wetland area—D'Olive Bay. This bay is located in the northeastern corner of Mobile Bay, Alabama (Fig. 4) and, over a period of some 15 years during which development of the subdivision took place, suffered an average depth loss of over some 70 cm as a result of sediment runoff from the subdivision.

Studies carried out by the Alabama Water Improvement Commission (Carlton and Gail, 1980) and the Soil Conservation Service (Crisler, 1981) clearly showed that

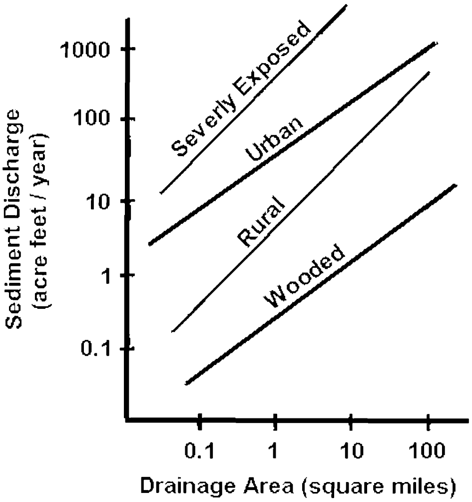

Fig. 3. Expected sediment discharge (annual) for various size Watershed areas (U.S.G.S. Open File Report, 1972, compiled by Weld et al., 1973).

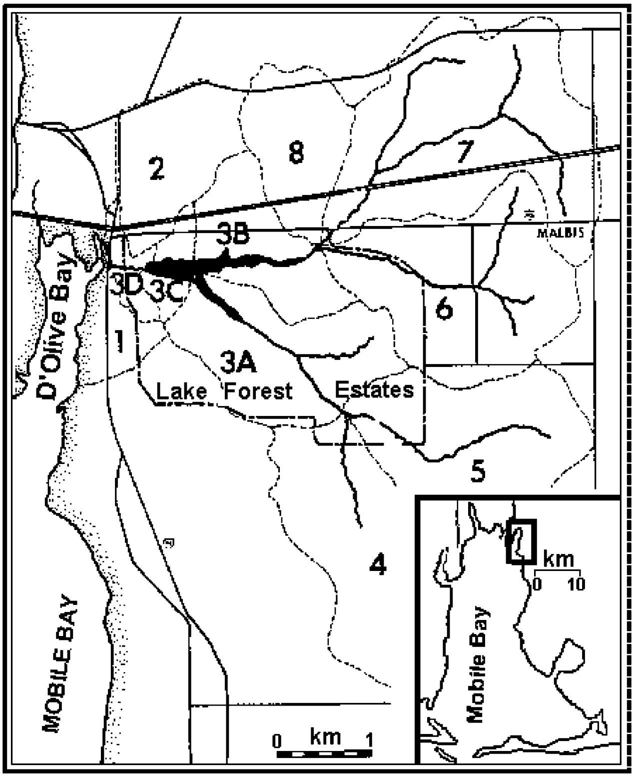

Fig. 4. Location map showing areas draining into D'Olive Bay. Lake Forest Estates subdivision includes 3A, 3B, 3C and 3D. Area shown in black is Lake Forest.

erosion in the D'Olive Bay drainage area had increased by an amount estimated at six times as great as those previously occurring when the area was largely farm and pasture land. Land development by Lake Forest developers, however, was done in a manner that even more greatly exacerbated erosion because over 48 km of streets were created in the subdivision and many of these remained unpaved for long periods of time (see Table 5 and Figs. 5 and 6). Similarly, check dams designed to attenuate runoff were poorly maintained (Fig. 7) and failed to prevent large amounts of sediment from being deposited initially in Lake Forest, but ultimately in D'Olive Bay.

Efforts by local and state agencies to force the developers to address the erosion problem met with only limited success and extensive erosion continued to cause large amounts of sediment to be deposited in the bay. Threats by property owners to file suit against the developers were countered by their contention that, because the bay is connected by its south entrance to Mobile Bay and because dredging had earlier taken place just to the north of D'Olive Bay during construction of Interstate Highway 10, no way existed to determine the degree to which erosion from the subdivision had impacted the bay. The U.S. Army Corps of Engineers, who had become involved in the controversy, contacted the author and asked if he thought that there might be a way of identifying the source(s) of sediment in the bay, and the

Table 5. Lengths of paved versus unpaved roads in Lake Forest Subdivision (Modified after Crisler, 1981)

Year	Miles of unpaved roads	Miles of paved roads
1971	35	3
1974	27	11
1975	17	21
1976	10	28
1980	6.6	31.4

Fig. 5. Oakland Drive, Lake Forest Subdivision (Photo: John Carlton, June 10, 1979).

degree to which the bay had been affected by construction activities in the subdivision. The author advised the Corps that any significant change in the sediment regimen of a drainage area must leave its record, in some form, in the deposited sediments (unless these sediments were later removed by erosion). This record might be in the form of: (1) an abrupt change in the particle size distribution of sediments analysed from cores, (2) possible changes in the mineralogy of core samples as new units are exposed by erosion, (3) changes in the carbon and sulphur content of the sediments as a result of increased (or decreased) oxidation rates and (4) changes in sediment chemistry, similarly brought about by erosion as new units are exposed. In the D'Olive Bay situation (1) and (2) above offered the strongest likelihood of allowing the depth in cores at which "impact" began to be recognised. This arose from the fact that, prior to development of the subdivision, most of the sediments in D'Olive Bay would have been derived from the periodic tidal currents that brought material from Mobile Bay into D'Olive Bay. Mobile Bay sediments originate from materials being brought into the bay by the Alabama-Mobile, the nation's fourth largest river system (exceeded, in discharge, only by the Mississippi, Columbia and

Fig. 6. Aerial view showing unpaved road in Lake Forest Subdivision (Photo: S. Coleman, June 22, 1979).

Fig. 7. Collapsed check dam in Lake Forest Subdivision (Photo: J. Carlton, August 31, 1979).

Yukon rivers) that brings sediment from the Piedmont, Ridge and Valley, Cumberland Plateau and Coastal Plain Provinces of southeastern United States. This produces a clay mineral suite dominated by smectite, and to a lesser extent, kaolinite and illite. The location on which the subdivision is developed, in contrast, is underlain by sediments belonging to the Miocene Ecor Rouge Formation and the

Plio-Pleistocene Citronelle Formation. Both of these units lack smectite and are composed chiefly of kaolinite, with lesser amounts of illite. The heavy mineral populations differ similarly. Sediments carried into Mobile Bay from northern and central Alabama contain a mineral suite that is rich in igneous and metamorphic minerals derived from crystalline rocks in the Ridge and Valley and Piedmont Provinces. The Miocene and Plio-Pleistocene sediments on which the subdivision is built were derived largely from reworking of older Coastal Plain Province sediments. Consequently, even though pre-impact and post-impact sediments might be made up largely of the same minerals, the percentages of these minerals would be expected to differ significantly. Given this information, the author was asked to collect necessary cores and samples to see if these conclusions could be substantiated.

The result came as no surprise to anyone familiar with geological processes. The expected abrupt change in clay mineral percentages was clearly evident in core samples taken throughout D'Olive Bay (see Isphording et al., 1984), as was also a marked change in the heavy mineral population. Core samples collected below the impact boundary were made up of particles whose grain size ranged from fine to medium sand (50–225 μm); those from above the boundary varied from clay size to medium silt (4–50 μm). The finer grain size of material from above the boundary was a simple consequence of the fact that larger particles were trapped behind the dam that was constructed to form Lake Forest. Consequently, only smaller particles were deposited in the bay from material washed over the spillway. Mineralogically the boundary was also apparent. Samples from below the boundary invariably contained less than 20% kaolinite (i.e. were very rich in smectite); those from above the boundary typically contained up to 40% (or more) kaolinite.

Analysis of the heavy minerals from samples from above and below the impact horizon provided further strong evidence that the boundary was a real entity. Even though the same minerals were used in the analysis of samples from above and below the boundary, the powerful statistical analytical procedure known as Discriminant Analysis clearly indicated that a different mineral population exists in samples from above versus below the boundary. The mathematical objective of a discriminant analysis is to "weigh" and compare variables from two (or more) groups and to then linearly combine the weighting in a manner such that the groups are forced to be as statistically different as possible (see Isphording and Flowers, 1980). This operation thus acts to transform the measured values obtained for all variables in a given sample into a single discriminant score that can be plotted on the resulting discriminant line. The transformation can therefore be envisioned as a search for an orientation in multivariate space where the two (or more) groups show the greatest separation, and the least dispersion. For the D'Olive Bay problem, each discriminant score plotted on the discriminant function (discriminant line) represents a weighting of the percentage of all the minerals in a single sample. When all samples from above and below the impact boundary are plotted (see Fig. 8) a clear separation is seen. From a statistical standpoint this would indicate that there is little doubt as to the presence of a distinct boundary, and the position identified for the boundary.

Table 6 shows the results of the discriminant analysis and identifies the discriminating variables that were most effective in separating the two groups, i.e. "pre-impact" and "post-impact" samples. Samples from above the impact boundary were statistically higher in tourmaline, rutile, kyanite and leucoxene; those from below the

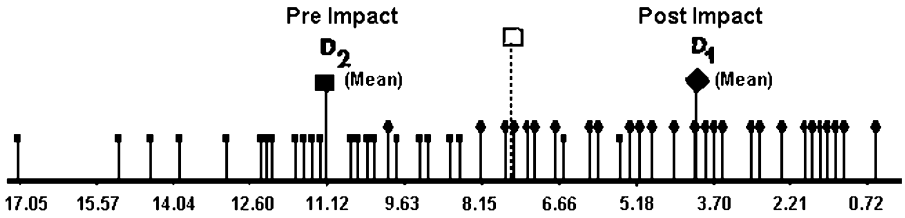

Fig. 8. Plot of discriminant scores (D) from heavy mineral analyses for "pre-impact" and "post-impact" D'Olive Bay core samples. D_1: average discriminant score for Group 1 (post-impact samples); D_2: average discriminant score for "pre-impact" samples. Open square is average value for all samples from both groups.

Table 6. Results of discriminant analysis for "pre-impact" versus "post-impact" samples

Variable	Mineral	Constant*	Per cent**
1	Epidote	−3.292	−28.67
2	Garnet	−4.532	−1.38
3	Hornblende	−5.202	−59.37
4	Kyanite	−5.416	227.37
5	Pyrite	−5.291	42.44
6	Rutile	−5.581	220.76
7	Sillimanite	−5.013	13.35
8	Staurolite	−5.188	5.89
9	Tourmaline	−5.760	144.87
10	Zircon	−5.471	89.15
11	Ilmenite	−5.170	−556.46
12	Leucoxene	−5.431	226.00
13	Tan Opaques	−4.743	−263.95

Notes: F-Test results: $F_{(13,42,.05)} = 2.00$ (value from F tables); $F_{(\mathrm{calculated})} = 2.64$. Conclusion: Reject null hypothesis H_0: $D_1 = D_2$. The two groups are statistically different at the 0.05 level of significance.

*Predictive coefficients used in the discriminant equation.

**Variables preceded by negative sign are "associating" variables; those with a positive sign are "discriminating" variables that best serve to separate the two groups.

boundary were statistically lower in these minerals. Samples for comparison were chosen from each group by using a random number generator in order to not introduce bias into the analysis. A total of 32 samples were used from above the boundary and 23 from below the boundary. In all cases, at least 300 heavy mineral grains were counted for each sample.

The information obtained from heavy mineral analysis, combined with the clay mineral percentages and the size analysis data, was mutually supportive and allowed the impact horizon to be identified in core samples from a series of traverses taken across the bay. It was clear from the results that erosion from the subdivision had, over the period of 15 years, caused the bay to lose an average depth of slightly over 60 cm. When apprised of the results of this investigation, no further attempt was made by the developers to contest responsibility for in-filling of the bay.

While the technique (discriminant analysis) used in this example may be foreign to some geologists, it is included to demonstrate that even when the same minerals are analysed from two groups, statistical procedures exist that may permit their differentiation. Further, discriminant analysis can be applied to other types of investigations involving heavy minerals and was successfully used to identify an apparent conformable relationship between two adjacent stratigraphic units in the New Jersey Coastal Plain (the Miocene Kirkwood Formation and overlying late Miocene-Pliocene Cohansey Sand) and an unconformable relationship between the Late Miocene Ecor Rouge Sand and overlying Plio-Pleistocene Citronelle Sand in south Alabama (see Isphording and Flowers, 1980). The failure of a discriminant analysis to find a significant difference between the percentages of minerals present in overlying and underlying units would be interpreted, statistically, as indicating that all samples were drawn from the same "population". Geologically, this would indicate not only that both units were derived from the same provenance area, but also that no significant time gap(s) had taken place during the depositional process (i.e. a "conformable" relationship exists). Where a major diastem exists between two units, however (i.e. an "unconformable" relationship), and even if the two formations were derived from the same provenance area, it is unlikely that the same ratios and percentages of heavy minerals would be present in sediments from the two stratigraphic horizons.

4. SUMMARY

The five cases described illustrate just some of the ways that heavy minerals can be used to aid in the solution of geological problems and social controversies. Heavy minerals not only are indicators of provenance, but also serve as an important "fingerprint" for the stratigraphic unit from which they are obtained. Unlike particle size analyses, which can vary widely within the same formation as a result of facies changes, and unlike clay mineral analyses that necessitate a sample possessing a clay fraction, the heavy minerals in a sample from a given unit generally do not vary greatly, as long as the same size fraction is examined. As such, they are a valuable tool in the geologist's arsenal of useful analytical methods.

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