PROCEEDINGS

OF THE

SIXTH SYMPOSIUM

ON THE

GEOLOGY OF THE BAHAMAS

Edited by

Brian White

Production Editor

Donald T. Gerace

Bahamian Field Station
San Salvador, Bahamas
1993

Printed in USA by Don Heuer

ISBN 0-935909-43-5

COMPARATIVE SEDIMENTOLOGY: BITUMEN PELLETS AND LUMPS IN MODERN AND ANCIENT SHALLOW WATER CARBONATE DEPOSITS, BAHAMAS AND NEW MEXICO

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ABSTRACT

As already noted by many interdisciplinary workers, petroleum residues, both natural and artificial, are common contaminants in the sea. Following two major tropical storms in the South Atlantic, bunker bitumen was driven ashore on the east coasts of the Bahama Islands and admixed with modern carbonate sediments and affixed to a solid substrate.

The behavior of this bitumen was studied along the Atlantic margin of Eleuthera Island, Bahamas. This bitumen is particulate, in both solid and semisolid form. The particles have been physically deformed, chemically degraded, and depositionally segregated on the basis of size and density. Carbonate sediment and certain marine biological organisms, including calcareous skeletons, have become selectively adhered to the bitumen particles. These traits, both depositional and diagenetic, probably simulate the behavior of natural bitumens discharged into the sea over geologic time.

Geologically, such material may provide evidence for paths of petroleum migration, exposure, and processes of degradation. The chronology and sequence of these events may be documented. Transformation may also influence the course of diagenesis and provide distinctive attributes which contrast with conventional water-based cementation events subsequent to depositional burial.

Eleuthera bitumen samples provisionally confirm the prospective usefulness of these criteria to more ancient examples. The Permian Seven Rivers Formation, New Mexico and its included residual hydrocarbons are examined briefly as a possible analog.

INTRODUCTION

Bunker oil, hereafter called bitumen, is a common artificial contaminant of seawater. It is viscous petroleum residue discarded into the sea by commercial shipping. This residue, together with those sourced in natural seeps or resulting from accidents or environmental neglect associated with commercial trade, is receiving increased attention by contemporary environmental scientists and geologists. In addition to the modern occurrences, viscous to solid bitumens present in numerous Phanerozoic strata have had the attention of geologists for many decades. The literature is too vast for a review here. For some modern examples and overview see: Blumer (1972); Kolpack, et al (1973); Natl. Acad. Sci.(1975); Morris and Butler (1973); Walker et al (1976); Am Petroleum Inst. (1977); and Zsolnay (1978), among many others. For a review of the nature of materials, both recent and ancient, see Ekman (1869); Pratt (1915); Abraham (1945); Labout (1950); Zubov (1960); Vernon (1963); Pilpel (1968); Horn (1970); Landes (1973); Davies (1976); Jacob (1983); and Parnel (1988), among many others.

The purpose of this paper is twofold. First, the characteristics, behavior and depositional significance of residual bitumen as "sediment" in a carbonate-dominant, marine setting is considered. It is introductory in nature and quite preliminary. Second, a brief consideration of the significance of this modern case history to geological occurrences is put forward, employing a possible analog taken from the Permian Seven Rivers Formation (Guadalupian), New Mexico.

Globules of bitumen are initially lighter in density than seawater. They are carried by marine currents and the tide to the shore where they become progressively heavier from weathering and from the acquisition of denser, inorganic sand grains by the tacky residue. Eventually the bitumen is stranded and buried as pellets and lumps in contemporaneous beach sediments or plastered on exposed bedrock. Most beaches adjacent to major shipping lanes receive periodic bitumen deposits. The eastern shoreline of the Eleuthera Island, Bahamas, is an example (Fig. 1). Eastern Eleuthera faces major Atlantic Ocean shipping

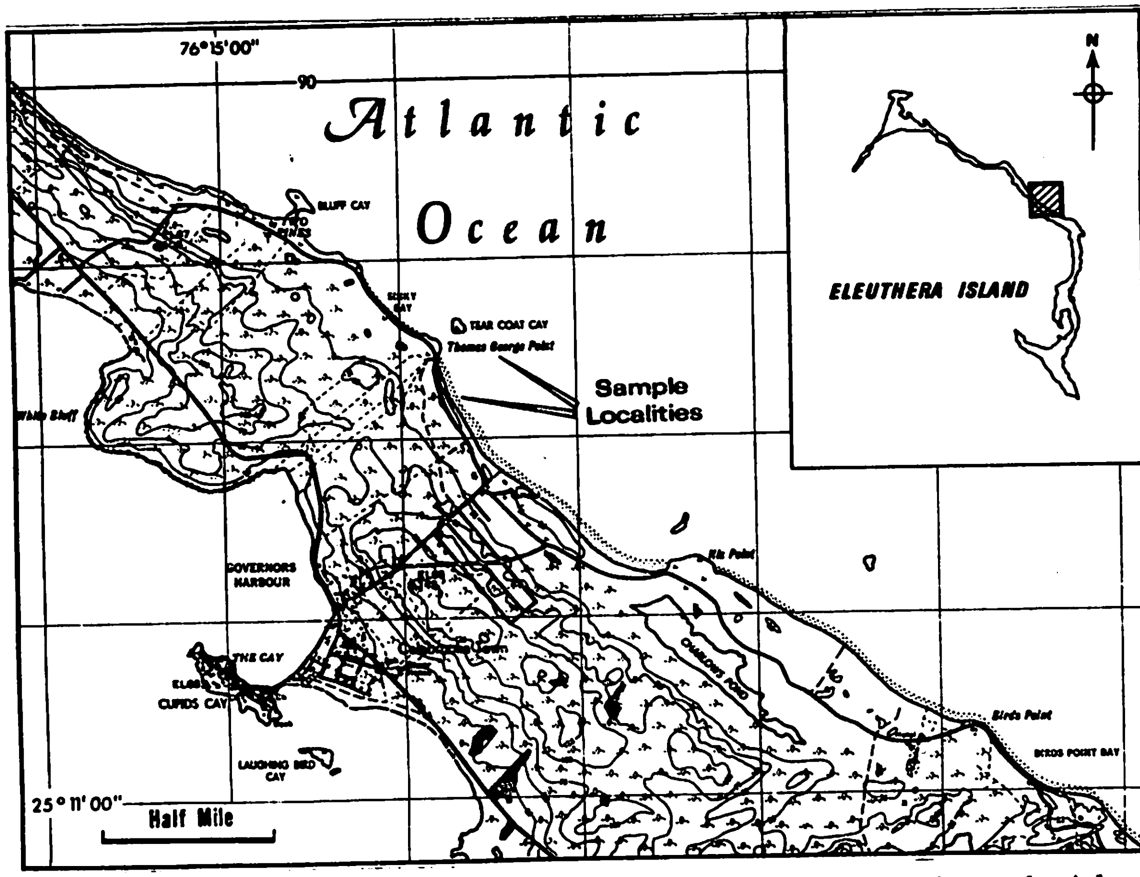


Figure 1. Map of portion of Eleuthera Island showing the sampling localities on the Atlantic Ocean side, opposite Governors Harbor.

lanes from which it occasionally receives deposits of semi-solid bitumen.

The behavior of bunker bitumen is probably analogous to some of the natural oils, pitches, and asphalt which become exposed to the action of seawater after they have migrated to the water/sediment interface. Sedimentary bitumen particles codeposited with carbonate grains are interesting from a positional point of view because they frequently enhance primary sedimentary structures. They also preserve the original mineralogy and morphology of many entrapped primary grains of metastable sediment. They are interesting from a petroleum exploration point of view because such deposits in the geologic record would be evidence for the migration of oil roughly contemporaneous with the deposition of the enclosing sediment.

The transformation to solid bitumen of migrating oil is itself of geological interest because the process may occur before, during, or after the associated carbonate sediment deposition, and will therefore contrast with and punctuate the depositional or diagenetic processes of the enclosing strata. The transforming bitumen will usually entrap any material with which it has come into contact. The process of transformation will provide a sealing condition for the retention of any skeletal index fossils and any radioactive elements and their disintegration products, either of which may be useful in the age-dating of an enclosing bitumen.

DEPOSITION OF BAHAMIAN BITUMEN PARTICLES

Figure 2A shows the site of deposition, south of Thomas George Point on the east shore of Eleuthera Island, Bahamas. At this location there is a wide, low profile beach, rising to a small unconsolidated storm berm and succeeded shoreward by small sand dunes. Eleuthera carbonate beach sands are predominantly coralgal in composition, with a significant contribution by the red encrusting foraminifera, *Homotrema rubra*. The frequency plot of Figure 3 confirms a medium grain size predominance of the sand with an arithmetic mean of ~ phi = 1.3. See Table I for size data.

Particles of soft bitumen may be water-borne over extremely short or long distances to the deposi-

Fig. 2. Co-depositional carbonate sand and solid bunker bitumen on the east shore of Eleuthera Island, south of Thomas George Point. Photos are of sequential depot sites up the beach profile, A-D.

A. Upper beach deposit of carbonate skeletal sand. Swash deposit consists of *Sargassum* algae and bunker bitumen particles, both associated with sand blisters (arrow) and air vents within the beach.

B. Close view of the upper beach. Solid bitumen lumps (arrows) are deposited close to the air vents (lower left). Vents are surface evidence of underlying "keystone vugs". Ocean is to the left.

C. Storm beach berm showing well-developed keystone vugs comprising fenestral texture. Small bitumen pellets are sparsely scattered within the deposit. Vugs result from air bubbles attempting unsuccessfully to escape water-buoyant sediment during single swash event. Ocean is to the right.

D. Unsorted bitumen particles lying as a lag deposit between storm berm and beach dunes. Finer bitumen "pellets" are being winnowed away at the top of the picture. Dunes are to the left.

tional locale. Gradual transformation of the bitumen to semi-solids or solids virtually assures the permanent retention of any material picked up and entrapped en route to the site of deposition. The entrapment of foreign material may hasten deposition if it is relatively heavy (e.g., inorganic crystalline grains) or may enhance further transport if lightweight material such as wood macerals or individually buoyant fauna or flora acquired *in vivo*, are the included matter. Figure 4 is a suite of photographs of modern bitumen particles showing the acquisition of heavier, skeletal fragments, such as grains of the green alga *Halimeda*, coral, and mollusca; and the buoyant float bladders of the brown algae, *Turbinaria* and *Sargassum*, the latter including one individual completely encrusted with a bryozoan. Such diverse acquisitions by accretion during transport result in the development of an "aggregate" particle and overall volumetric enlargement. The net effect of these acquisitions may be to add to, or subtract from, the ultimate depositional density of such candidates for bitumen sedimentation in the shallow water environment. Bitumen particles or their complexes are not products of mechanical attrition. On the contrary, they commonly become enlarged by coalescence with other bitumen particles. Their range in size is therefore greater than that for the associated carbonate grains which are incorporated from the unconsolidated sedimentary substrate.

Rounded and occasionally flattened bitumen particles are usually deposited on modern beaches and

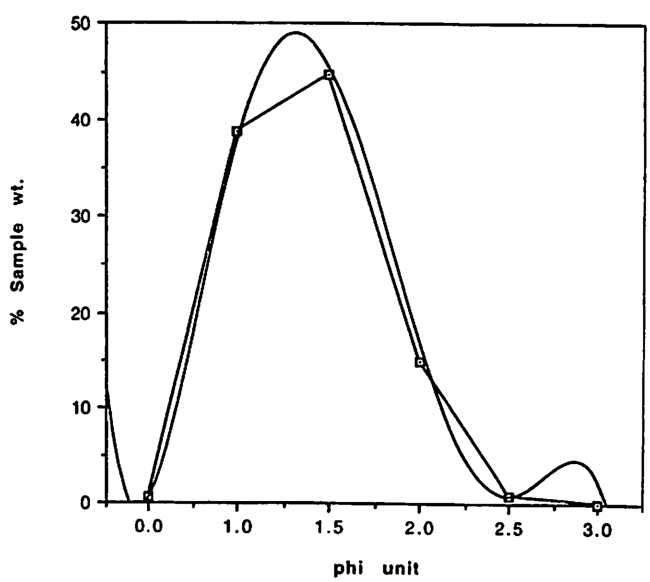


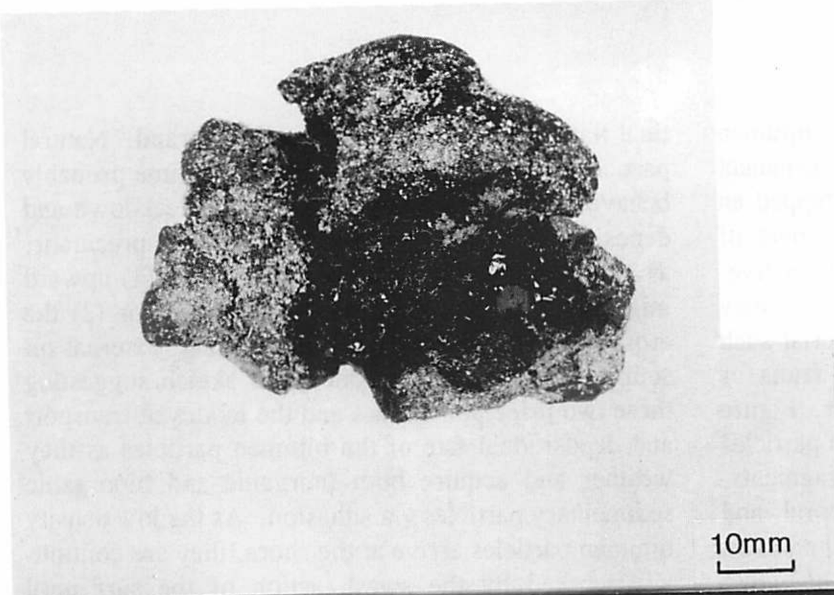
Fig. 3. Frequency plot of carbonate sand-sizes for the Eleuthera beach shown in Figure 2. The smooth curve is fifth order polynomial fit.

tidal flats just above or just below the strand. Natural particles occurring throughout geologic time probably behaved in a similar way. Before the breakdown and deposition of natural particles of bitumen, a precursor, as oil, may have been released initially by (1) upward migration to the sediment/water interface, or (2) the erosion of pre-existing oil-bearing strata (external oil source). Figure 5 is a conceptual sketch suggesting these two principal sources and the modes of transport and depositional fate of the bitumen particles as they weather and acquire both inorganic and bioorganic sedimentary particles via adhesion. As the low density bitumen particles arrive at the shore, they are continually worked by the swash action of the surf until stranded on the beach by a waning tide, (Fig. 2B). During strong weather events, bitumen lumps may be driven beyond the normal high tide line, to and across the beach berm where the larger particles become permanently stranded (Fig. 2D).

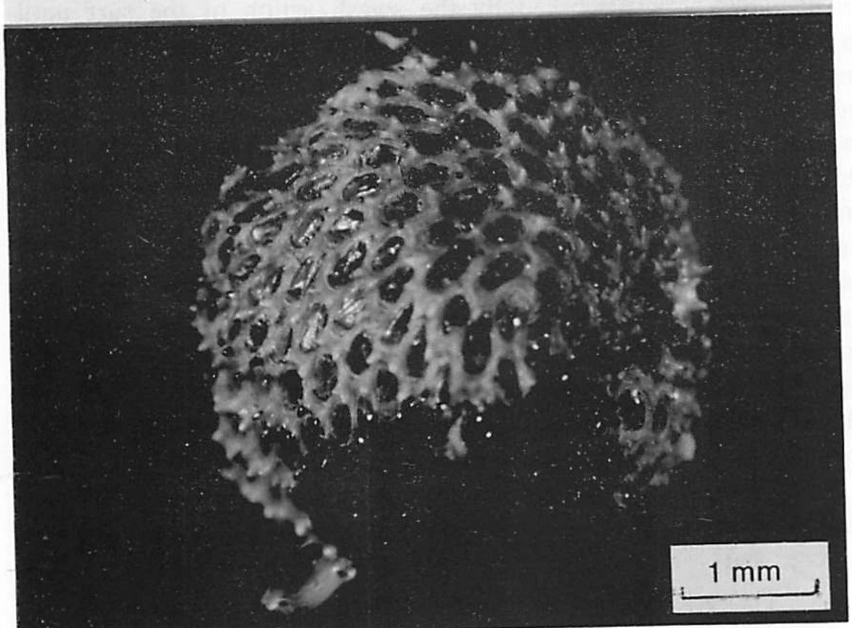
The location of storm beach bitumen deposits observed on the east shore of Eleuthera Island is usually at and beyond the exposed shoreward wedge of fenestral strata (Fig. 2C) comprised of keystone vugs (Dunham, 1970). The bitumen particles become crudely size-sorted, as very large lumps are retained as lag deposits, while smaller particles are transported further by the wind and are worked into small beach dune sediment (upper left of Fig. 2D). Dune bitumen particles appear to be uniformly small, usually less than 20mm (Fig. 6). The manner of formation of the proximal fenestral fabric is revealed in contemporary strand development by the occurrence of surficial vent holes and sand blisters on the wetted beach, as first described by Emory (1945). These cavities form as a result of escaping air rising through a layer of porous sand previously wetted with interstitial sea water that percolates during ebb flow of the surf (Fig. 7). Air which fails to escape from below the surface bow up loose grains into keystone "arches" which are self supporting and thus aid in the preservation of porous cavities that have been designated keystone vugs. Such vugs are commonly preserved in ancient counterparts. Rocks of such origin are said to have a "bird's-eye" texture.

Below the low tide level, there is also a lag deposit of bitumen particles at the sediment/water interface. Their occurrence is related to their greater bulk density as discussed below. These particles are usually more extensively weathered, or weighted with inorganic grains, and have been picked up again

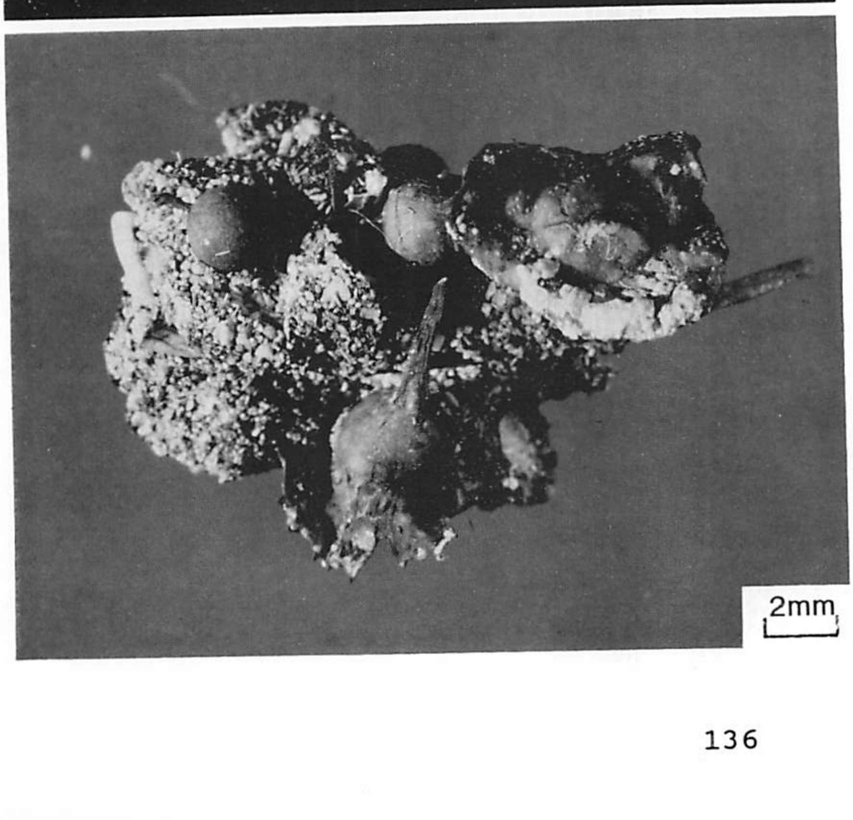
Beach-deposited solid bitumen lumps. East Eleuthera Island.



A. Bitumen lump showing surface accretion of calcareous sediment and sticky interior where artificially broken open. The trapped particle is a bryozoan-covered float bladder of the brown alga *Sargassum*.



B. Close view of Figure A., reflected light, showing bryozoan-covered float bladder of brown alga. The bryozoan was originally unstained before drying out. It was probably water-wet when first trapped.



C. Typical occurrence of bitumen as it floats with the aid of entrapped *Turbinaria* and *Sargassum* float bladders. The bitumen surface also has small calcareous sediment particles attached to it.

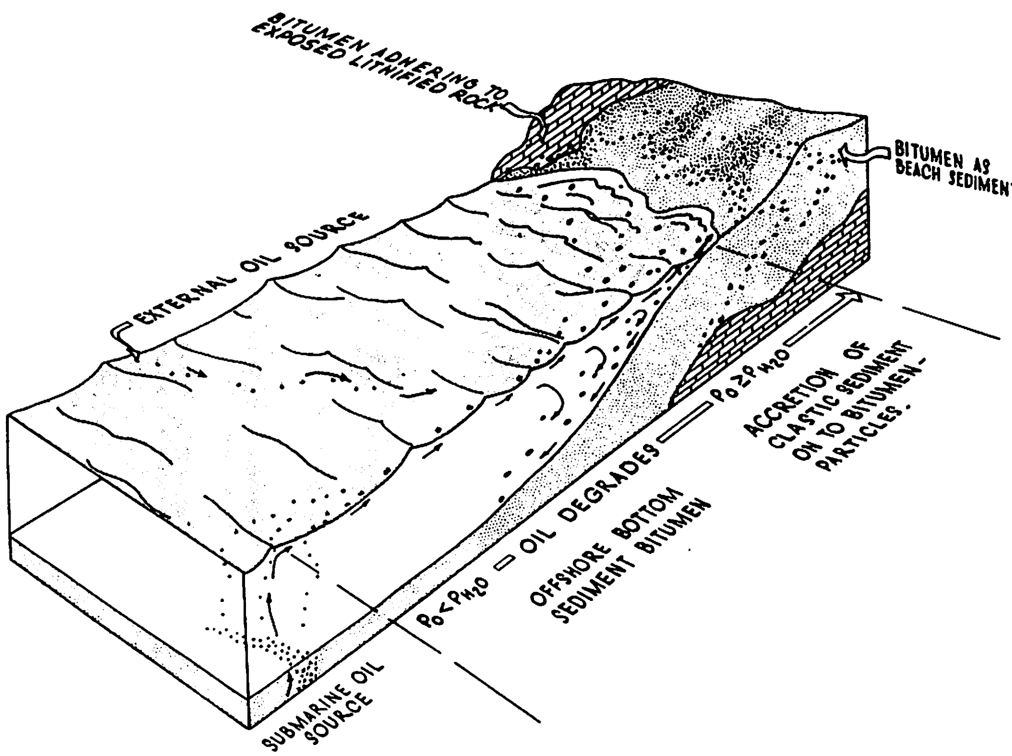


Figure 5. Block diagram suggesting multiple sources and depositional behavior of natural bitumen along marine shorelines.

several times by the surf after earlier exposure to weathering (transformation) on the beach.

Minor amounts of bitumen are also deposited directly on Eleuthera Holocene (?) reef rocks such as Tear Coat Cay which form small headlands protecting the beaches. The bitumen is plastered nearly flat like a wad of chewing gum (Figs. 8A-C) with a few calcareous grains attached to the upper surface. In the geological record, such an occurrence would be directly associated with unconformities and facies boundaries. Doubtless such an occurrence in the stratigraphic record would be difficult to recognize since diagnostic criteria would be obscured through renewed burial.

FACTORS AFFECTING DEPOSITIONAL DENSITY

Chemical Composition

An elemental chemical analysis was obtained for bunker bitumen deposited on Eleuthera beach in order to validate its superficial resemblance to natural bitumen (Fig. 9). Bunker bitumen is generally comparable to a natural bitumen but is dissimilar in that it possesses a low fixed carbon content which is attributable to its incomplete transformation.

In addition to low fixed carbon content the Eleuthera bitumen is slightly richer in sulfur and ash than some natural asphaltites but not asphaltic pyrobitumens. The latter are those defined as nearly insoluble in organic solvents and carbon disulfide (CS_2). The data confirms that the modern bitumen from Eleuthera is quite soluble in CS_2, with a value of 68.1%, yet it also has a high ash content typical of many pyrobitumens. This ash content is atypical of most such measures because of the presence of many carbonate grains and other insoluble particles which were completely engulfed by the sticky bitumen and thus were not removed by acidization before analysis as were those grains adhering to the surface alone. The literature suggests that the analysis of the Eleuthera bitumen is representative of most modern bunker bitumen that is contaminating the sea surface and which originates from crude oil tankers and other similar vessels which discharge tank washings and ballast into well-travelled sea lanes.

A chromatographic analysis of the bitumen reveals a highly altered residuum, particularly the low boiling range, which is most likely the result of microbial degradation (Fig. 10). There is a marked

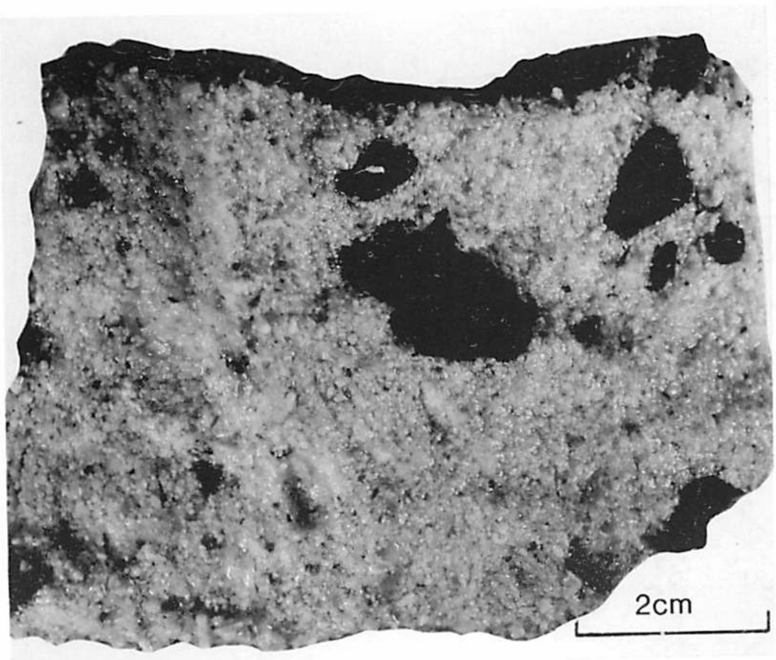


Fig. 6. Photo of the vertical parting surface of a core of the modern, unconsolidated carbonate beach, showing early burial, and random size and distribution of bitumen.

Fig. 7. Vent holes and sand blisters on the upper beach which result as entrapped air rises through water-saturated sand following ebb-flow in the swash zone.

absence of normal carbon number peaks, through and including the isoprenoids. Considering the high solubility of the sample, the high background signal of the chromatographic trace probably represents a complex of aliphatic chains of high carbon number. Though informative, the chromatograph represents the measure of only one sample, and from only one subenvironment. Many similar analyses are required so as to assess the range of chemical properties of such material and their possible relevancy to ancient, natural geological materials of similar composition.

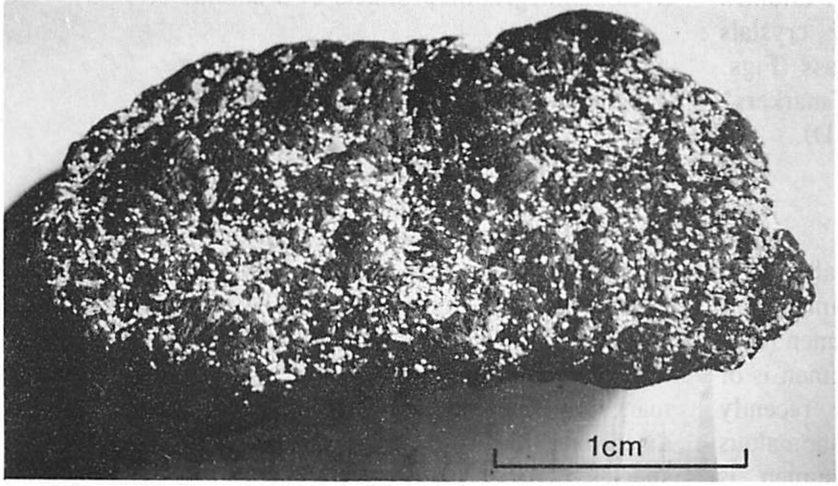
Physical Properties

Since depositional density can be markedly affected by the extent of chemical transformation, the densities of 48 samples were determined for comparison with bitumen particles occurring in different parts of the shoreline environment (Fig. 11). The samples were first leached with dilute hydrochloric acid to remove carbonate grains. Greater sampling would be desirable but it is clear that beach-deposited particles have a greater range of value, many of which are far above a seawater value of $\pm$ 1.025. As previously noted, a source of potentially large error is the retention of many carbonate grains that are preserved totally within the bitumen masses and thus not accessible to chemical digestion. Individual variations of normal ash content probably exist and would contribute along with other entrapped matter, to the variations in measured density. Also, the relative weight added by calcareous grains originally adhering to most of these bitumen particles may offset significantly any variation in the true bulk density of the bitumens with respect to their potential energy requirement for marine transport by ocean currents.

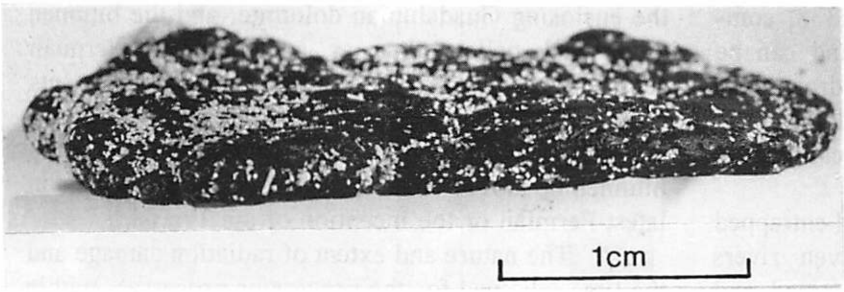
The size and shape of bitumen particles have an important effect on the depositional density because they influence the number of attached grains of carbonate, the aggregate of which weigh down the lighter density bitumen. If all bitumen particles were spherical and their surfaces covered uniformly with carbonate grains, the surface-to-volume ratio would dictate that a larger particle would naturally receive a greater relative contribution to total density from the bitumen portion. Of course, the bitumens are not spherical at all and furthermore, most surfaces are incompletely covered with carbonate grains.

To examine the importance of the surface grains to depositional density as a function of particle volume, the surf-suspended and beach-deposited

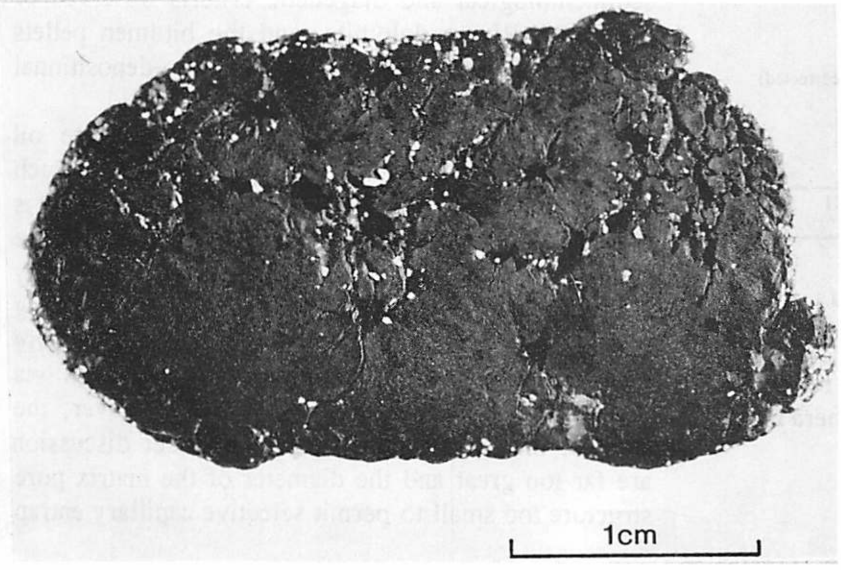
Fig. 8. Photos A, B, and C are top, oblique and bottom views respectively, of a flattened bitumen lump taken off Holocene reef bedrock, Tear Coat Cay, Eleuthera. Most of the calcareous grains have been incorporated onto the upper surface. The lower surface retains several large voids were the lump failed to come into contact with the bedrock.



A. Top view.



B. Oblique view.



C. Bottom view.

bitumen particles in Figure 11 were analyzed for percent weight loss attributable to dissolution of surface calcareous grains by acidization (Table II). The semilog plot of Figure 12 employs the reciprocal percent grain weight and indicates that for both the surf-suspended and beach-deposited bitumen particles, those of larger volume receive less density contribution via surface grains. The departure of the data from any linear distribution is predictable (1) because the larger bitumen particles deviate markedly from sphericity and have highly variable amounts of carbonate grains on their surfaces, and (2) because the carbonate grains are nearly as large as the smallest bitumen particle. Hence the surface grain attachment cannot be considered merely a surface coating throughout the size range.

COMPARATIVE SEDIMENTOLOGY: ATTRIBUTES OF THE PERMIAN SEVEN RIVERS FORMATION BITUMEN

General Description

Bell (1956), has briefly described the Seven Rivers dolomite (Permian, Guadalupian) in Rocky Arroyo, San Andres Mountains, New Mexico, which contains "asphalt pellets and botryoidal masses" encased as solid matrix inclusions. There are also occurrences of several other morphologic modes, both diagenetic and petrophysical. The field location is the same as cited as a restricted facies location by Dunham (1972) see Fig. 13. The analyses and interpretation of these several occurrence types have been summarized (Roehl, 1986; Roehl and McLaughlin, 1988). However, detailed description and documentation of these types is beyond the scope of this paper and will be reported separately. The pellets however have possible relevance to the contemporary (co-depositional) sedimentology under discussion.

Briefly, the "pellets" are of diverse shapes and sizes (Figs. 14A-D). They are all black, solid, amorphous mineraloids (impsonite) that occur as isolated particles within a wackestone or packstone groundmass, comprised principally of dolomitized pelletoidal, pisolitic or occasionally stromatolitic texture. Most bitumen pellets are larger, commonly much larger, than the particle fabric of the dolomite, with the exception of uncommon pisolitic clasts. These pellets contain fine, isolated detrital crystal fragments of quartz and more rarely, feldspar. Commonly original crystal forms are still manifest, save for minor rounding (Fig. 14A). Larger bitumen particles possess suites of detrital quartz crystals occupying the periphery of the bitumen mass (Figs. 14B-C), or, less commonly, as accretion "markers" within coalesced compound masses (Fig. 14D).

Chemical Composition

Virtually all constituent element values and physical properties of the Seven Rivers bitumen vary significantly from the modern Eleuthera bitumen (Fig. 15). This is expectable, since the latter bitumen is of artificial (unnatural) origin and has only recently become degraded and semi-solid. The anomalous sulfur content of the Seven Rivers bitumen is logarithmically related to an unusual content of uranium. The density of the bitumen is quite high, even after correction for ash content at 1.338, compared to most natural bitumen species, and can be attributed to a large fraction of non-hydrocarbons which have been incorporated. Radiation damage has undoubtedly contributed to the high fixed carbon and low hydrogen content of the material.

More than ninety percent of the lead entrapped within the bitumen particles of the Seven rivers Formation has been experimentally determined and result from the decay of U^{238} and U^{235} (Roehl and McLaughlin, 1988).

Density $^{20}_{4}$	1.15 (0.01 ash corrected)
Solubility CS_2	68.1%

	C_T	C_F	S	N	O	H	Ash
Average Composition in Weight %	71.6	14.6	3.4	0.7	3.1	9.1	13.2

C_T, C_F = Total and fixed carbon, respectively

Fig. 9. Elemental chemical analysis of recent co-depositional bunker bitumen, Eleuthera Island.

Useful uranium/lead ratios were also determined and are given in Figure 15. The remarkable generation and survival of radiogenic lead is possible because of the unique chemical and physical properties of the host amorphous organic complexes, which result in the efficient entrapment of the many and sequential, short-lived disintegration products of uranium.

Factors Affecting Deposition in Time and Space

Uranium-Lead Age Dating

Ratios for U^{238}/Pb^{206} and U^{235}/Pb^{207}, cited in Figure 15, provide a unique opportunity to determine a date of closure of the bitumen, wherein all disintegration products must be permanently retained. Had any such products escaped the system over geologic time, the resulting ratios of Figure 15 would have been markedly different and attributable to the markedly discordant half-lives of the two uranium isotopic species. As it is however, there is a remarkable concordance of the two age dates. Until recently, such dates would have confirmed the chronological age of the enclosing Guadalupian dolomite, and the bitumen globs and pellets thus as contemporary Permian sediment! However, recent international refinements on the age of the Permian-Triassic boundary necessitate that the closure (seal) date of the uranium-bearing bitumen be moved ahead to a post-depositional time in latest Permian or the inception of the Triassic.

The nature and extent of radiation damage and the time involved for the process or processes, within the confines of a hydrocarbon (bitumen) complex, are very poorly understood. Notwithstanding these facts, sedimentological and diagenetic criteria observed of the Seven Rivers dolomite, and the bitumen pellets contained therein, strongly support a co-depositional origin for both.

Any other argument would necessitate oil migration within a pre-dolomitic pore structure. Such pore-centered oil occurs in the present dolomite, but is geologically younger and markedly dissimilar to the solid, heavy bitumen within the matrix. Capillary considerations require that cessation of non-wetting hydrocarbon flow would result in an expectable pore network geometry of entrapment of petroleum via imbibition. Notwithstanding this fact however, the sizes of the solid bitumen particles under discussion are far too great and the diameter of the matrix pore structure too small to permit selective capillary entrap

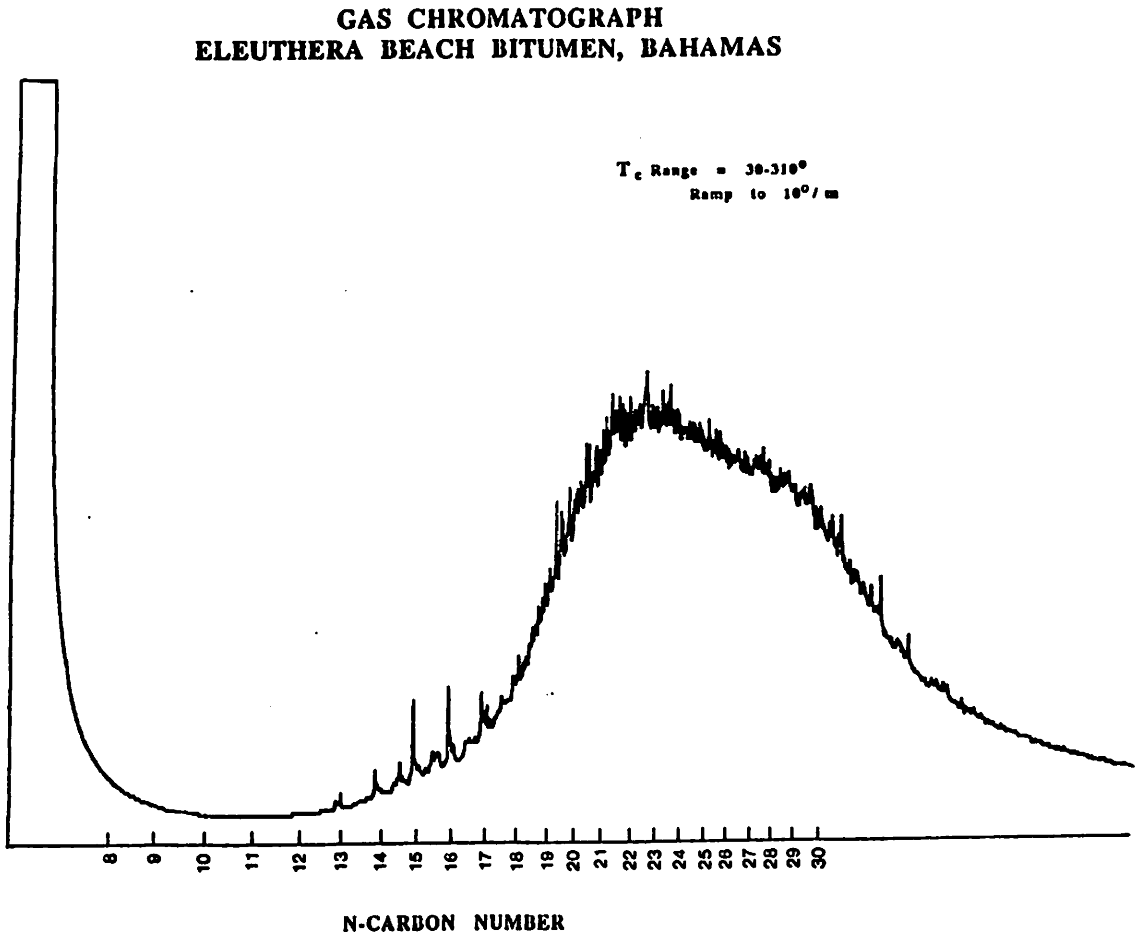


Fig. 10. Gas chromatograph of a beach-deposited bitumen from south of Thomas George Point, Eleuthera.

Number of Samples	Description	Density (ρ_o) Range (ρ_o)	Avg. ρ_o
16	Beach-deposited bitumen	0.97^5 - 1.75^5	1.29
16	Offshore, bottom bitumen	0.99 - 1.38	1.07
16	Surf-suspended bitumen	0.95 - 1.07	1.01^5

Fig. 11. Density values of bitumen particles grouped according to their subenvironments.

ment of many large quartz and feldspar fragments (e.g. Fig. 14A).

Sedimentary Considerations

Non-carbonate crystal fragments occur almost exclusively within the mineraloid bitumen particles and were probably derived from the adjacent shelfward facies that was comprised principally of aeolian sand and evaporite sediments (Fig. 13). The intraparticle predominance of those fragments and their distinctive geometry of entrapment by the bitumen suggests that the entrapment occurred early, during the period of transition of the hydrocarbon from a fluid to a viscous solid. The crystal fragment distribution is similar but not identical to the carbonate grain distribution present on many of the modern Eleuthera bitumen particles. both resemble "armored mud-balls". However the quartz crystal fragments differ because they are not of the same mineralogy as the external host sediment matrix of the rock. In addition, the majority of the crystalline quartz fragments appear to be engulfed, rather than embedded, along the margins of the bitumen particles. Based on the observable textural

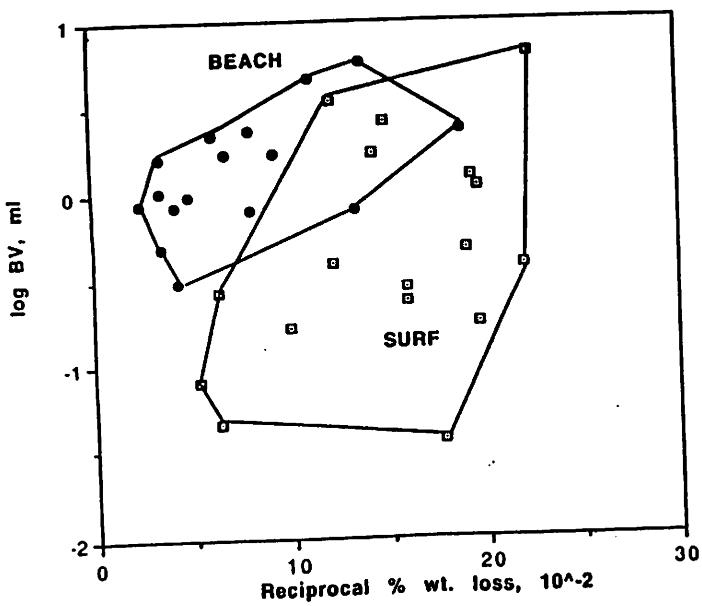


Fig. 12. A semi-log plot of the volume of individual bitumen particles following acid removal of attached carbonate grains, compared to the reciprocal percent weight loss attributable to the grains.

relationships, the Seven Rivers bitumen pellets appear to have incorporated the quartz crystal grains, either preferentially during transport along the floor of the shallow Permian sea just prior to deposition, or more likely from clastic-dominant sands of the flanking peritidal environment of aeolian sand and evaporite. If true, the acquisition would be prior to their transport into the seaward locale of carbonate predominance in which they are now found. Because of pervasive dolomitization, it is difficult to discern whether carbonate grains were acquired by adhesion to the margins of the bitumen particles. However, the fine state of carbonate particle preservation together with an apparent absence of engulfed carbonate grains which would otherwise be discernable within the limited petrographic cross-section cuts so far observed (Fig. 14), seems to mitigate such occurrence.

Finally, Figure 14 shows a bitumen pellet, and three smaller satellites of similar aspect, intimately related to an algal(?) pisolite. These pisolites are of Permian contemporary origin and are most prevalent within and seaward of the subject sediment facies. Pre-pisolitic occurrence and acquisition of non-carbonate crystal fragments necessitates that the Seven Rivers matrix-bound bitumen pellets and irregular lumps be interpreted as co-depositional with their pelletoidal and pisolitic hosts. The bitumen precursor, as liquid petroleum, was therefore, probably sourced from seeps along a sandy, evaporitic, peritidal shoreline where quartz and feldspar were first encountered and entrained.

Before concluding, it should be noted that bitumen occurrences in ancient sedimentary strata must be very carefully studied on an individual basis and cannot be considered in the general context of normal sediment particle occurrences. What may prove true

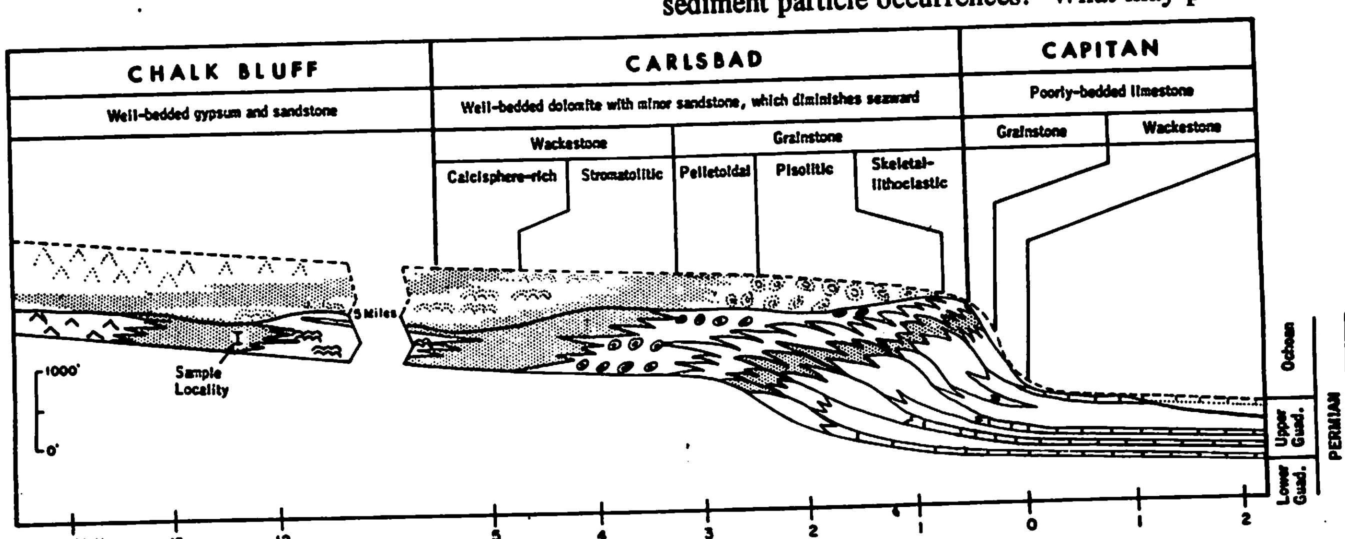
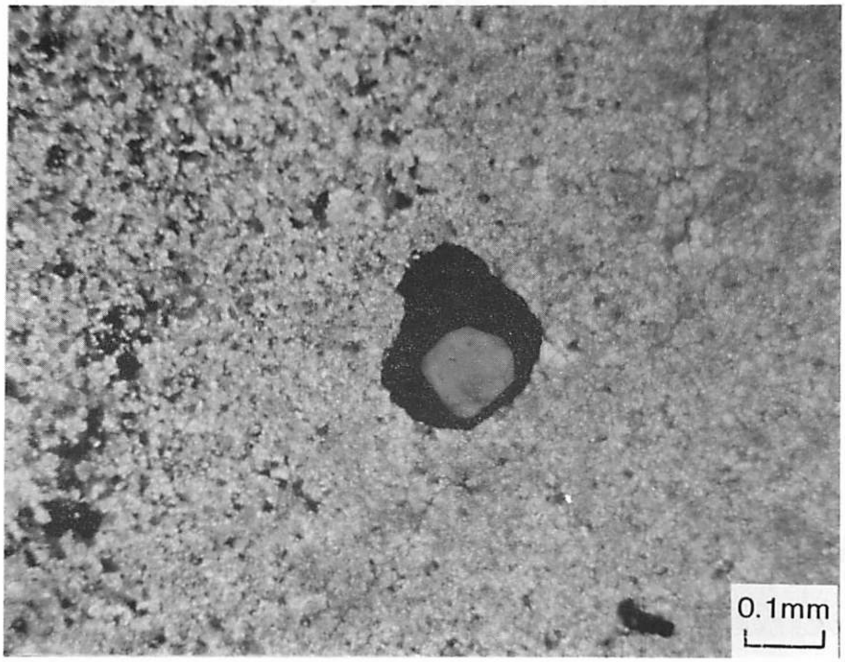
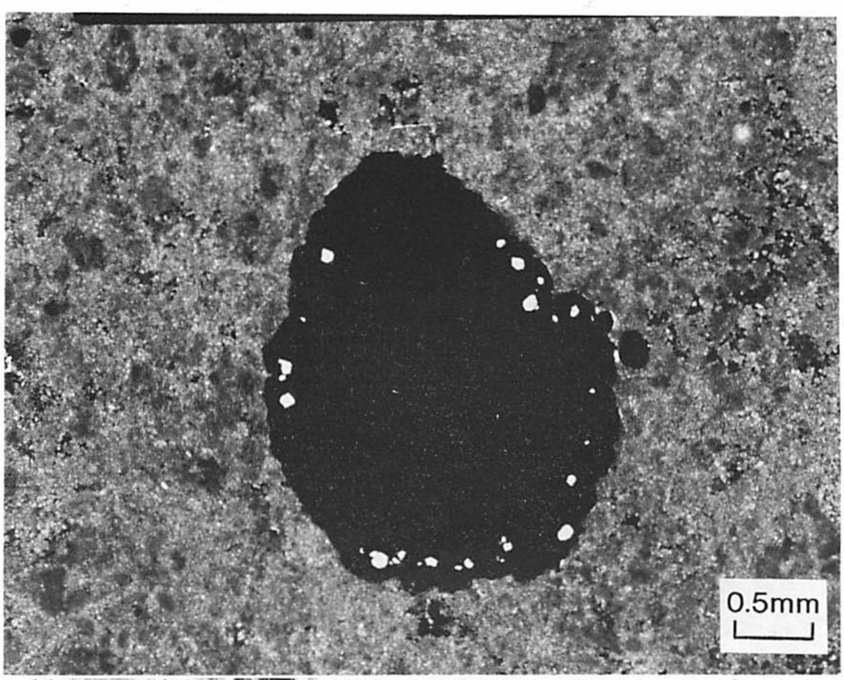


Fig. 13. Stratigraphic diagram taken from Dunham, 1972, which shows the facies locations and relationships of Upper Guadalupian strata. The sample locality I-5 of Dunham is the site where bitumen samples were obtained.

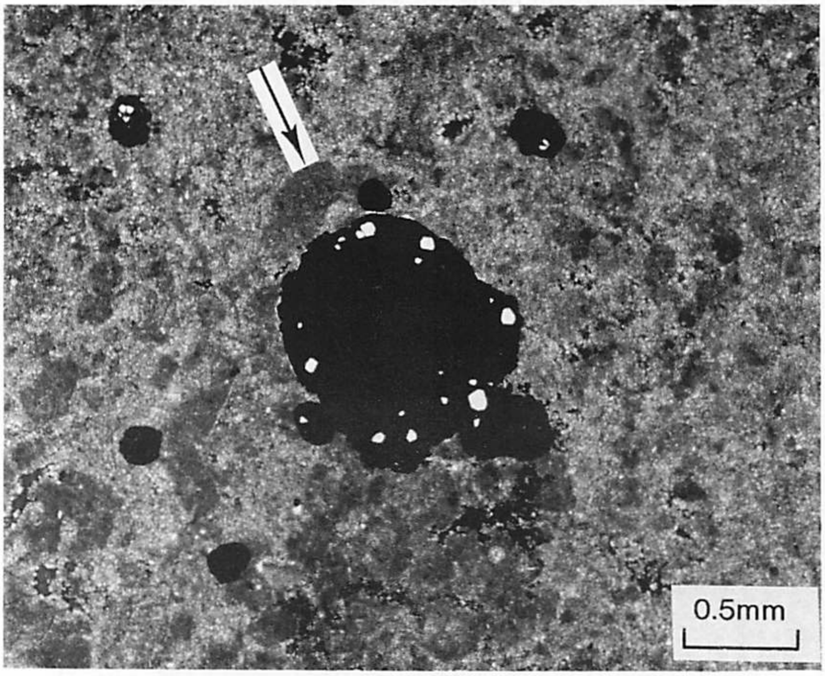
Fig. 14. Photomicrographs of bitumen in Seven Rivers dolomite which contain fragments of non-carbonate crystal grains, principally quartz. All photos in plane polarized transmitted light.



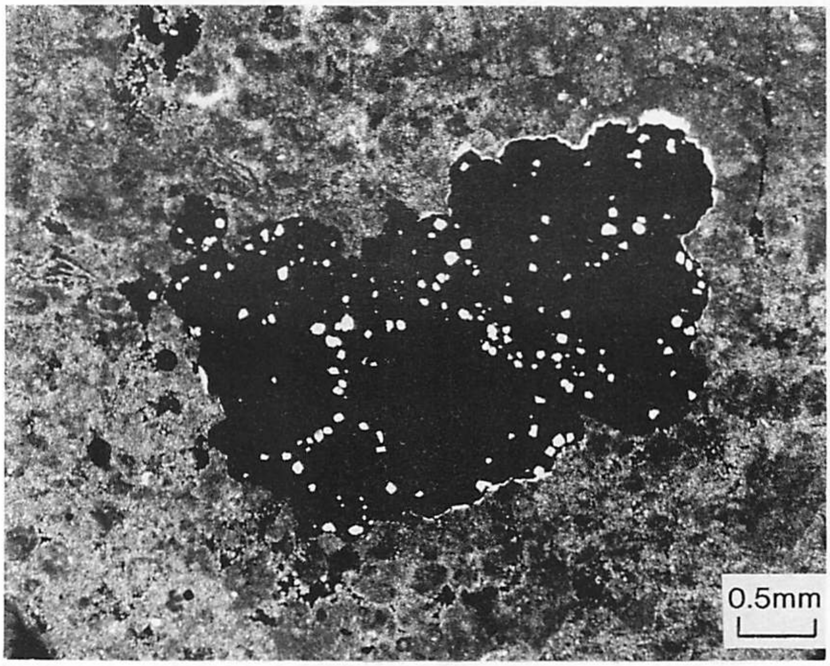
A. A large detrital quartz grain enclosed in a small bitumen pellet. The surrounding matrix is a dolomudstone. Size of grain precludes the possibility of its emplacement by transport, together with oil, through the rock pore structure.



B. Large bitumen globule in a relict pelletoidal carbonate matrix and displaying a peripheral concentration of adsorbed detrital quartz and feldspar grains which suggest a high viscosity during their emplacement.



C. Bitumen pellet similar to Figure 13B, but with additional smaller, satellite bitumen globules, which have accreted to the larger mass. Arrow indicates margin of a much larger clotted carbonate particle, an algal(?) pisolite (criteria not presented) which has in turn captured smaller globules of bitumen.



D. Pelletoidal and lithoclastic wackestone containing a large compound bitumen mass. Disposition and geometry of quartz crystal fragments suggests coalescence of several previously independent pellets similar to that of Figure 13C.

TABLES

Table I. Data set of values determined for the weight percent frequency distribution of Eleuthera Island beach sands according to grain sizes occurring above high tide. See text Figures 2 and 3.

phi size	% sample weight	% cumulative weight
0.0	0.520	0.520
1.0	38.910	39.430
1.5	44.880	84.310
2.0	14.860	99.170
2.5	0.780	99.950
3.0	0.050	100.000

Table II. Data set of values for Eleuthera Island bitumen particles retrieved from the beach berm and surf subenvironments of Eleuthera Island, south of Thomas George Point. Bulk volume values of bitumen, following acid digestion, are tabulated against a reciprocal measure of the respective values of carbonate grain weight removed by the acidization. See text Figures 11 and 12.

SURF SAMPLES			BEACH SAMPLES		
BV,ml	log BV,ml	R % loss	BV, ml	log BV,ml	R % loss
0.045	-1.347	6.400	0.304	-0.517	4.300
0.080	-1.097	5.350	0.489	0.311	3.500
0.164	-0.785	10.000	0.800	-0.097	13.400
0.174	-0.759	19.600	0.798	-0.098	8.000
0.233	-0.633	16.000	0.864	-0.063	4.200
0.281	-0.551	16.000	0.890	-0.051	2.400
0.265	-0.577	6.400	0.971	-0.013	4.900
0.385	-0.415	22.000	1.045	0.019	3.500
0.398	-0.400	12.200	1.620	0.210	3.400
0.480	-0.319	19.000	1.710	0.233	6.800
1.100	0.041	19.600	1.720	0.236	9.300
1.260	0.100	19.300	2.180	0.338	6.200
1.710	0.233	14.300	2.290	0.360	8.100
2.580	0.412	14.900	2.320	0.365	8.800
3.430	0.535	12.200	4.550	0.658	11.200
6.510	0.814	22.400	5.700	0.756	13.800

$Density^{20}_{4}$	1.429 (1.338 ash corrected)							
Solubility CS_2	8.2%							

	C_T	C_F	S	N	O	H	Ash	$U_{(ppm)}$
Average Composition in Weight %	60.9	51.6	18.5	0.5	7.1	4.6	8.0	14.7×10^3

C_T, C_F = Total and fixed carbon, respectively

Radiometric Age (m.y)

U^{238}/Pb^{206}	U^{235}/Pb^{207}
$228 \pm 10 \times 10^6$	$228 \pm 15 \times 10^6$

Fig. 15. Chemical, physical and radiometric properties of solid matrix bitumens. Seven Rivers Formation.

of one bitumen occurrence type, may bear no relationship to another preserved in the same strata.

CONCLUSIONS

Pellets and lumps of bunker bitumen are common deposits on modern beaches and rocky shores. Their behavior may be analogous to some natural bitumens in ancient rocks. The bitumen deposits on Eleuthera occur (1) above the high tide as beach berm and dune deposits, (2) below low tide as lag debris, and (3) as adhesions to solid beach rock. Bitumen particle density is variable, being related to ash content, foreign matter (usually fauna, flora or their skeletal remains to which it is adhered), and degree of bitumen transformation. Bitumen particles may emphasize certain features of sedimentary fabrics, for example cross-bedding. They may also deform after deposition and lose their character when they coalesce with other bitumen particles, thus forming an interstitial stringer of bitumen. Because of its affinity for uranium, recognition of radioactive, co-deposited bitumen and determination of its date of closure with respect to retention of daughter isotopic decay species, may help to determine dates of petroleum movement and the age of the enclosing strata. The same may be said for bitumen found enclosing index fossils.

Requirements for the deposition and preservation of recognizable, primary, naturally occurring bitumen particles appear to be:

1. A source or proto-bitumen, probably from a submarine oil seep or the contemporary erosion of oil-bearing rock.

2. A bitumen particle density value in excess of seawater resulting from inspissation of the parent oil, microbiological degration, and/or the accretion of heavier sand grains onto the bitumen particle.

3. A preservable geometry which can be easily associated with the depositional processes of the enclosing inorganic sediment and which appears to be unrelated to secondary oil entry into the pore structure of a lithified host rock.

ACKNOWLEDGEMENTS

The author's attention was first focused on the uniqueness and geologic importance of "natural asphaltic substances" by George Edwards and William McLaughlin of Shell Exploration and Production Research in 1960, when they reviewed the significance of the uranium content of the Seven Rivers Formation bitumen. Bill McLaughlin's uranium analyses have been pivotal to the author's studies. Several other workers have been of great assistance and support in the field: Maitland Bethel (Bahamas), Robert Dunham, and George Moore. Shell Research, Unocal Research and Worldwide Resources, Inc. provided field and analytical support.

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