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INDUCED COLOR IN OSTRACODE SHELLS: AN EXPERIMENTAL STUDY

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Abstract.—Color alteration and the origins of the dark colors in ostracode shells were investigated. Modern shells were subjected to temperatures and pressures (T-P) simulating some burial conditions. Fossil shells were heated and immersed in solvents in an attempt to identify the coloring agents.

Shells of modern, marine ostracodes are white to pale yellow (Munsell 5Y 8/1 to 2.5Y 8/4). Upon heating, up to 650°C, they became slightly redder, darker, and less color-saturated but never dark (that is, they had Munsell value greater than 5). Above 650°C they became even lighter and more yellow, and above 850°C still more yellow and chalky. Shells at elevated T-P with organic-poor sediments or iron compounds developed higher color values and low chromas but did not become dark. Only those heated in organic-rich sediment and crude oil became dark (grays, browns, and blacks), resembling fossils from some outcrops and wells.

Shells near igneous intrusions have dark colors, and the darkness and color-saturation of fossils in metamorphic rocks correlate with increasing paleotemperatures. Reheated dark fossils lighten at about 375 to 450°C; the coloring agent was driven off. This and the fact that modern ostracodes develop dark colors only when heated in organic-rich substances support the contention that the dark color originates from extraneous organic materials. The colors seem diagnostic of T-P and sediment and present the possibility of their use in reconstructing paleotemperature.

Key words: Ostracoda, shell color, diagenesis, paleotemperature, experimental, low-grade metamorphism.

INTRODUCTION

Interpretations of geologic history based on fossils would be enhanced if taphonomic processes were better known. Included in such processes are induced color changes that take place in shells and other durable parts of organisms (Tway *et al.,* 1986). Conodonts and pollen are well known in this regard; their color changes have been carefully studied, and systems have been devised to interpret the thermal history of the fossils and the containing rock or sediment (Epstein *et al.,* 1977; Rejebian *et al.,* 1987; Wilson, 1961). Similar applications for microscopic calcareous shells have been the subject of recent studies that are still in their early stages (Kontrovitz *et al.,* 1988; Kontrovitz *et al.,* 1989).

Unlike previous articles on ostracodes, the present study addresses color alteration under temperatures and pressures (T-P) that simulate some conditions of diagenesis and metamorphism. Various types of sediment were used, thereby introducing another variable.

MATERIALS AND METHODS

Modern, unaltered, marine ostracodes (Oertli, 1971) from Florida Bay, U.S.A., and the beach of Rimini on the Adriatic Coast of Italy were used. Modern, freshwater

Table 1. Modern taxa used in experiments to induce color.

Peratocytheridea setipunctata (Brady)*
Cytherura sandbergi Morales*
Xestoleberis sp.*
Loxocorniculum fisheri (Brady)*
Radimella sp.*
"Hemicytherideis" elongata (Brady)†
Cytheretta judaea (Brady)†
Loxoconcha rubritincta Ruggieri†
Hiltermannicythere turbida (Müller)†
Candona sp.‡
Ilyocypris sp.‡
Cypridopsis sp.‡

* Florida Bay, Florida Keys, U.S.A.
† Beach of Rimini, Italy
‡ Bayou Desiard (freshwater), Monroe, Louisiana, U.S.A.

forms were obtained from Bayou Desiard at Northeast Louisiana University (NLU), Monroe, Louisiana (Table 1). Fossils were recovered from outcrops in northeastern Spain and boreholes in Mesozoic and Tertiary rocks from Zaire, Gabon, Senegal, and Irish and United Kingdom offshore areas (see Ainsworth *et al.*, 1990).

Tests at atmospheric pressure were done in an oven and furnace on a platinum substrate with or without sediment. Diagenetic and metamorphic changes were better simulated at elevated T-P in reactor vessels (Temp-Pres MRA-114S) with appropriate volumes of water or crude oil and water to obtain the desired pressures. Heating was done with flexible heating tapes (Thermoline, 312 watts) wrapped around the vessels, with a proportional electronic temperature controller (Versatherm Model 3156-4) and independent thermocouples used to control and monitor temperatures within less than 2°C of the desired setting. [See Kontrovitz *et al.* (1982) for details of the methodology.]

For most experiments with reactor vessels, T-P increments of 30°C and 100 atmospheres (atm.) were used throughout the range of 120 to 300°C and 400 to 1000 atm. These approximate T-P average values for burial depths of 4 to 10 km (Garrels & Mackenzie, 1971); other T-P combinations are given in Tables 2, 4, 8, 9, 12, and 13.

Experiments with shells in reactor vessels were done with 0.25 g of sediment, which included pure quartz, calcite, or a chlorite, illite, and mixed layer illite-smectite clay (herein called Elf clay). Some trials included mixtures of the sediments and other materials mentioned below, including organic-rich, natural sediment from the freshwater Bayou Desiard, which contains 12.8 percent organics (loss on ignition; Gross, 1971). After each experiment, shells and sediment were recovered from the vessels and air-dried; the shells were then isolated for examination.

The authors speculated that petroleum may be a coloring agent for calcareous shells; this was based on their finding colored ostracode shells in petroliferous rocks. Therefore, a series of tests was performed with crude oil at elevated temperatures at atmospheric and higher pressures.

Colors of treated and untreated shells were described with the standard Munsell Soil Color Charts (1988). On these charts color is the combination of hue, value, and chroma, each of which has a separate notation. The notation for hue gives its relation to red, yellow, green, blue, and purple; the notation for value indicates its lightness; and the notation for chroma indicates its strength (or "departure from a neutral of the same lightness"). For example, in the Munsell notation 5YR 8/3, hue is given by 5YR; value is 8; and chroma is 3.

In addition to the color charts with standard notations for hue, value, and chroma, Munsell provides accompanying cards with names of colors of soils. These cards give such names as white and olive gray, which correspond to fields represented by the standard notations. The names, however, are less precise than the notations; for example, light gray is used both to summarize areas that include several different standard notations on a single card and for areas on several different cards. This is shown by the colors designated by standard notation as 5YR 7/1 and 5Y 7/2, which are both named light gray even though 5YR 7/1 is redder and the less color saturated of the two. It is suggested that the reader will find it useful to have the color and name charts at hand while reading this paper.

Shells were placed on a Munsell standard, gray masking card and viewed through a Wild M-5 binocular, stereomicroscope set at a magnification of 20X. The stage was illuminated by two American Optical model 651 lamps, each set at intensity level 2, about 15 cm from the specimens. One lamp was placed on each side of the microscope stage, so that the two lights and the specimen were on a straight line parallel with the front of the stage.

Fossil shells were examined, subjected to heating, and immersed in organic solvents in an attempt to gain information about the coloring agents. Colors of fossils from

Table 2. Colors of modern, marine ostracode shells after 48 hours at temperature listed and atmospheric pressure.

Temp. (°C)	Munsell notation	Color
100	5Y 7.5/2	light gray
200	5YR 6.5/2	pinkish gray
250 – 275	5YR 5.5/2	reddish gray
375 – 425	5YR 5.5/1	gray
475 – 525	5YR 5.5/1	gray
575 – 625	5YR 5.5/1	gray
650 – 675	5YR 8/1	white
685 – 735	10YR 8/1 to 10YR 9/1	white
775 – 825	10YR 9/1 to 10YR 7.5/2	white to light gray
875 – 925	2.5Y 7.5/2	light gray
975 –1025	5Y 7.5/1.5	light gray

Table 3. Colors of modern, marine ostracode shells subjected for 48 hours to the temperature and pressure (T-P) indicated, in the sediments listed.

T-P (°C, Atm.)	Quartz	Calcite	Elf clay
120, 400	5Y 8/1 (white)	2.5Y 7/4 (pale yellow)	2.5Y 8/0 (white)
150, 500	5YR 8/1 (white)	2.5Y 8/0 (white)	2.5Y 8/2 (white)
180, 600	5Y 8/1 (white)	2.5Y 8/0 (white)	2.5Y 7/2 (white)
210, 700	5Y 8/1 (white)	2.5Y 6.5/4 (light yellowish brown)	2.5Y 8/2 (white)
240, 800	5Y 8/1 (white)	2.5Y 8/2 (white)	2.5Y 8/0 (white)
270, 900	5Y 7.5/1 (light gray)	5YR 8/1 (white)	2.5Y 7.5/2 (light gray)
300, 1000	5Y 9/1 (white)	2.5Y 6/2 to 2.5Y 8/0 (light brownish gray)	2.5Y 7.5/2 (light gray)

Table 4. Colors of modern, marine ostracode shells subjected for 48 hours to T-P listed, in 25% calcite and 75% quartz.

T-P (°C, Atm.)	Color	P (Atm.)	Color	P (Atm.)	Color
120, 400	10YR 7.5/2.5 (light gray)	200	2.5Y 7.5/2 (light gray)		
150, 500	10YR 8/3 (very pale yellow)	200	5Y 9/1 (white)		
180, 600	10YR 6.5/2 (light gray brown)	200	5Y 8/1 (white)		
210, 700	10YR 8/1 (white)	200	5Y 8/1 (white)		
240, 800	10YR 8/1 (white)	200	5Y 8/1 (white)		
270, 900	10YR 7.5/2 (light gray)	200	2.5Y 7/2 (light gray)	2000	10YR 8/1 (white)
300, 1000	5YR 6.5/1 (gray)	200	10YR 7.5/1 (light gray)	2000	10YR 9/1 (white)

Table 5. Colors of modern, marine ostracode shells subjected to different T-P in the sediments listed.

T-P (°C, Atm.)	90% calcite 10% siderite	75% calcite 25% siderite	90% calcite 10% hematite	100% hematite
120, 400	5YR 7.5/1 (white)	10YR 7.5/2.5 (light gray)	2.5Y 8/3 (white)	10YR 8/1 (white)
150, 500	5YR 8/2 (pinkish white)	5YR 8/1 (white)	2.5Y 6.5/3 to 2.5Y 5.5/4 (light yellowish brown to light olive brown)	7.5YR 8/2 to 5YR 8/2 (pinkish white)
180, 600	5YR 7.5/2 (pinkish gray)	10YR 6.5/2 (light brownish gray)	2.5Y 6.5/4 (light yellowish brown)	No recovery
210, 700	10YR 7.5/2 (light gray)	10YR 8/1 (white)	2.5 Y7/1 (light gray)	5YR 5.5/3 (fragile, reddish brown)
240, 800	5YR 8/1 (white)	10YR 8/1 (white)	2.5Y 7/2 (light gray)	No recovery
270, 900	5YR 8/0 (white)	10YR 7.5/2 (light brownish gray)	10YR 7.5/3 (pale brown)	No recovery
300, 1000	No recovery	5YR 6.5/1 (gray)	5YR 9/1 (white)	10YR 7/2 (light gray)

Table 6. Colors of modern, marine ostracodes tested in organic-rich (12.8%) bayou sediment at T-P listed.

T-P (°C, Atm.)	Color
120, 400	——
150, 500	10YR 5.5/2 (grayish brown)
180, 600	2.5Y 5.5/2 (grayish brown)
210, 700	10YR 2.5/2 to 10YR 3.5/2 (very dark brown to very dark grayish brown)
240, 800	10YR 3/2 (very dark grayish brown)
270, 900	2.5Y 6/2 (light brownish gray) (?ostracode)
300, 1000	10YR 2/2 (very dark brown)

some outcrops were compared with colors of shells from rocks with known thermal histories to determine how temperature may alter shell color.

We herein define dark to mean those colors with Munsell values of less than 5 in the range from 0 to 10, which represent absolute black to absolute white, respectively (Munsell Soil Color Charts, 1988).

All specimens are housed in the Department of Geosciences, Northeast Louisiana University.

RESULTS AND DISCUSSION

Modern, untreated, unaltered, marine specimens are white (5Y 8/1 to 5Y 8/1.5) to pale yellow (2.5Y 8/4). Upon heating at atmospheric pressure up to about 650°C, they became redder in hue, darker (lower values) and lost color saturation (chroma); that is, shells changed to 5Y 7.5/2 (white or light gray) to 5YR 5.5/1 (gray) to 10YR 8/1 (white). Above 650°C and up to about 800°C they became lighter again and more yellow. Above about 850°C shells retained their general shape and outline and became even more yellow, chalky, or flaky (see Table 2). We interpret these changes to indicate that the materials in the organic network of the shell and the epicuticle (Bate & East, 1972) were driven off before the temperature reached 650°C and that calcite began to deteriorate at about 850°C (Gross, 1971).

Marine shells subjected to elevated T-P with pure sediments of either quartz, calcite, or Elf clay showed no overall tendencies to change hue, value, or chroma (Table 3; Figures 1,*10*–1,*11*). In 25 percent calcite and 75 percent quartz, at increments of 30°C and 100 atm., they became redder, darker, and more color saturated than untreated specimens; less alteration took place when the pressure was maintained at a low level, 200 atm. In trials at the highest pressure (2,000 atm.) the shells appeared to be severely bleached. Pressure, then, seems to have a positive relationship with the degree of alteration of color of the ostracode shell (Table 4).

As outlined in Table 5, marine shells in different iron compounds were also subjected to elevated temperatures and pressures. Shells in 90 percent calcite and 10 percent siderite became markedly redder in hue and their chromas increased up to 210°C (decreasing at higher temperatures), but they showed no significant differences in value. Shells treated in 75 percent calcite and 25 percent siderite became redder and showed no consistent trend in color value (lightness or darkness) or in chroma. In 90 percent calcite and 10 percent hematite, shells eventually became redder and less color saturated (chroma) with increasing T-P. In 100 percent hematite with elevated T-P, shells became redder and somewhat darker but showed little change in color saturation (i.e., overall the change was white to reddish brown to light gray). Although some alteration

Table 7. Colors of modern, freshwater ostracodes (*Cypridopsis* sp.) tested in sediment from Bayou Desiard with calcite as a control, at T-P listed.

T-P (°C, Atm.)	Calcite	Bayou sediment; some soft-parts in shells	Bayou sediment; without soft-parts in shells
120, 400	10YR 5.5/2 (gray)	——	10YR 4.5/3 (brown)
150, 500	5YR 8/1 (white)	10YR 5.5/2 (grayish brown)	2.5YR 3.5/2 (dusky red)
180, 600	10YR 8/1 (white)	2.5Y 4.5/2 (dark grayish brown)	2.5Y 4.5/4 (olive brown)
210, 700	10YR 8/1 (white)	7.5YR 3.5/0 (very dark gray)	5Y 2.5/1 (black)
240, 800	10YR 8/1 (white)	10YR 2.5/2 (very dark gray)	5Y 2.5/1 (black)
270, 900	10YR 8/1 (white)	10YR 2/1 (black)(?shell)	10YR 4.5/3 (brown)
300, 1000	10YR 8/1 (white)	No recovery	10YR 4.5/2 (dark grayish brown)(?shell)

? = probably

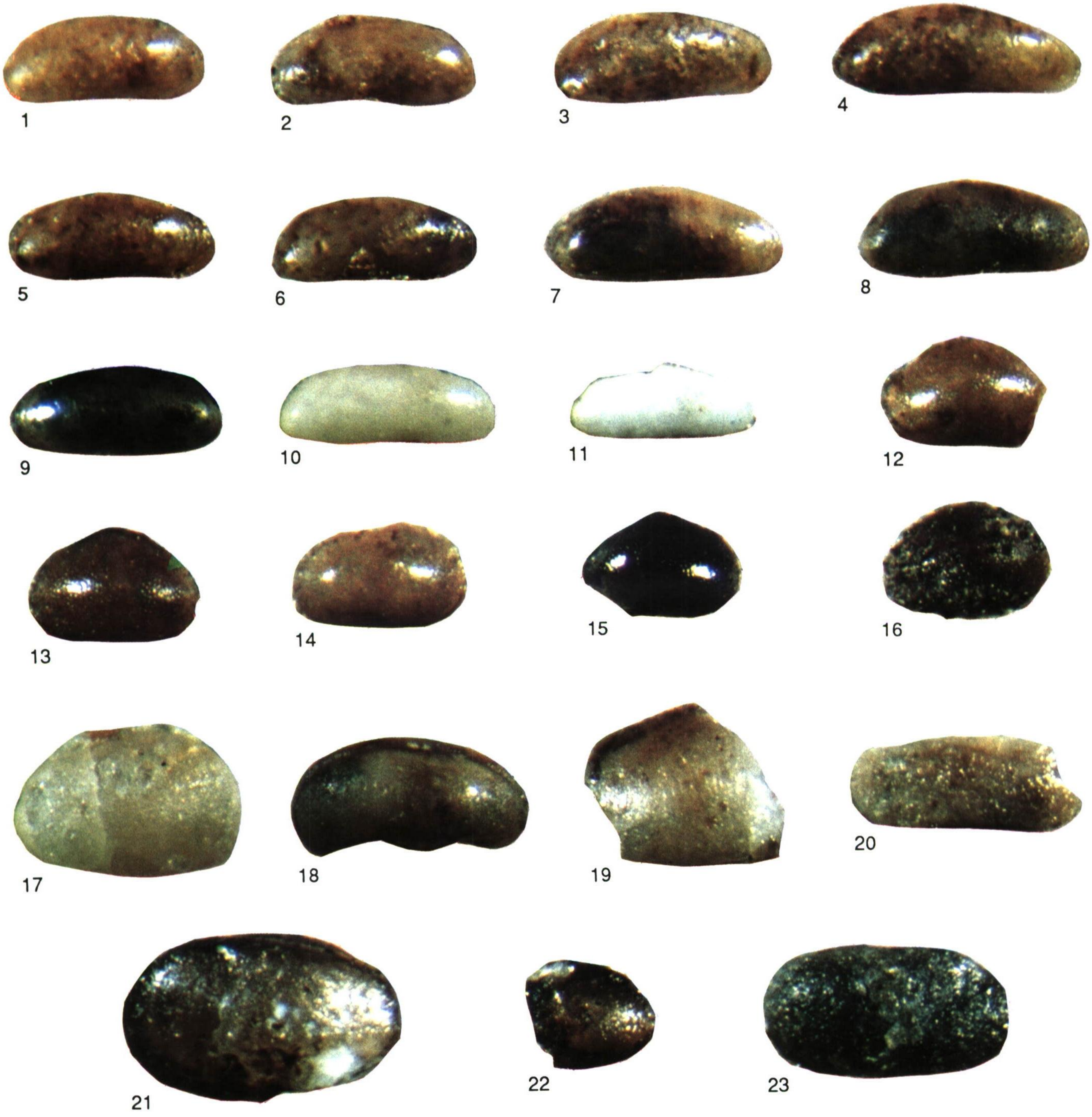

Fig 1. Individual specimens photographed on the Munsell gray mask card; photos were trimmed and mounted on Crescent Illustration Board #110 ("white"). All specimens shown at magnification of 45X.——*1–9. Hemicytherideis elongata* (Brady), treated at temperature and pressure indicated in quartz and crude oil; *1,* treated at 120°C, 400 atm., *2,* treated at 150°C, 500 atm., *3,* 180°C, 600 atm., *4,* 210°C, 700 atm., *5,* 240°C, 800 atm., *6,* 270°C, 900 atm., *7,* 300°C, 1000 atm., *8,* 330°C, 1100 atm., *9,* 360°C, 1200 atm.——*10–11. Hemicytherideis elongata* (Brady), treated in quartz and distilled water only; *10,* 120°C, 400 atm., *11,* 300°C, 1000 atm.——*12–16. Cypridopsis* sp., treated in organic-rich bayou sediment; *12,* 120°C, 400 atm., *13,* 150°C, 500 atm., *14,* 180°C, 600 atm., *15,* 210°C, 700 atm., *16,* 270°C, 900 atm.——*17–23.* Various Cretaceous ostracodes from Elf-Agip Congo borehole BGM-1; *17,* from depth of 1415–1440 meters, *18,* fragment, 1650–1660 m, *19,* fragment, 1920–1940 m, *20,* fragment, 2060–2070 m, *21,* 2125–2145 m, *22,* fragment, 2200–2210 m, *23,* 2455–2465 m.

Table 8. Colors of modern, marine ostracode shells heated in an oven at 50°C at atmospheric pressure, with crude oil (API 46°); sediments as listed.

Time (hours)	quartz	calcite	Elf clay
24	2.5Y 6.5/6 (olive yellow)	2.5Y 6.5/6 (olive yellow)	2.5Y 5.5/6 (olive)
48	2.5Y 4.5/2 (olive gray)	2.5Y 4/2 (olive gray)	2.5Y 5.5/2 (olive gray)
72	2.5Y 3.5/2 (dark olive gray)	2.5Y 4/2(olive gray)	2.5Y 5/2 (olive gray)
96	2.5Y 5.5/4 (olive)	10YR 4/3 (olive)	2.5Y 4.5/3 (olive)
120	2.5Y 5.5/4 (olive)	2.5Y 4.5/4 (olive)	2.5Y 6.5/4 (pale olive)
144	2.5Y 4.5/4 (olive)	10YR 4/4 (olive)	10YR 6/3 (pale brown)
168	2.5Y 6/4 (light yellowish brown)	10YR 4/4 (dark yellowish brown)	10YR 5.5/3 (brown)
192	2.5Y 5/4 (light olive brown)	10YR 3/6 (dark yellowish brown)	10YR 5/3 (brown)
216	2.5Y 6.5/2.5 (light brownish gray)	10YR 3/6 (dark yellowish brown)	10YR 5/3 (brown)
240	2.5Y 5.5/3 (grayish brown)	5YR 3.5/3.5 (dark red brown)	7.5YR 6.5/4 (light brown)
264	7.5YR 6.5/4 (light brown)	10YR 3.5/4 (dark yellowish brown)	7.5YR 4.5/4 (dark brown)
432	7.5YR 5.5/2 (brown)	10YR 3.5/4 (dark yellowish brown)	7.5YR 6/4 (grayish brown)

Table 9. Colors of modern, marine ostracode shells heated in crude oil (API 46°) at temperatures shown and atmospheric pressure.

Temp. (°C)	Quartz	Calcite	Elf Clay
190 to 200	10YR 4.5/3.5 (brown)	10YR 5.5/3 (brown)	10YR 6.5/3.5 (pale brown)
316 to 371	10YR 4.5/3 (dark brown)	10YR 5.5/3 (brown)	10YR 6.5/2 (light brownish gray)
371 to 425	10YR 7.5/1.5 (light gray)	10YR 5.5/1 (gray)	2.5Y 5.5/2 (grayish brown)

Table 10. Colors of modern, marine ostracode shells in calcite or quartz sediment, with crude oil (API 46°) at T-P listed.

T-P (°C, Atm.)	Calcite	Quartz
120, 400	——	2.5Y 6/4 (light olive brown)
150, 500	10YR 6.5/4 (light yellowish brown)	10YR 5/4 (yellowish brown)
180, 600	10YR 6.5/4 (light yellowish brown)	10YR 4.5/2 (dark grayish brown)
210, 700	10YR 5.5/4 (yellowish brown)	10YR 3.5/3 (dark brown)
240, 800	10YR 6.5/4 (light yellowish brown)	10YR 4.5/3 (brown)
270, 900	10YR 6.5/2.5 (light brownish gray)	10YR 4.5/3 (brown)
300, 1000	10YR 6/3 (pale brown)	10YR 2.5/2 (very dark brown)
330, 1100	——	10YR 3/1 (very dark brown)
360, 1200	10YR 8/1 (white)	5Y 2.5/1 (black)

was expected and attained with these iron compounds, the shells were *not* changed to the dark grays, dark browns, and blacks that characterize many fossil ostracodes. Indeed, at none of the temperatures and pressures in the experiments described above did the ostracodes change to the dark colors seen in some fossils.

Marine ostracode shells in the bayou sediment, which contains 12.8 percent organic matter, underwent changes that resulted in dark colors like those of some fossils. They became redder and darker but maintained the same chroma (2). Initially, specimens became grayish brown (10YR 5.5/2 to 2.5Y 5.5/2) from 150°C at 500 atm. to 180°C at 600 atm., while at higher T-P shells became very dark grayish brown to very dark brown (10YR 3/2 to 10YR 2/2) (Table 6).

Prior to testing, freshwater specimens were white to pale yellow (2.5Y 7.5/2.5). When mixed with sediment from Bayou Desiard and subjected to elevated T-P, freshwater ostracodes with soft parts (*Cypridopsis* sp.) became much darker and slightly less color saturated, then redder

Table 11. Colors of Early Cretaceous ostracode shells from the Yanguas-Arnedillo, northeastern Spain; paleotemperatures interpreted from metamorphic rocks. Temperature presumed to increase from top to bottom of table (temperature data from H. J. Oertli, personal communication, 1984).

Temp. (°C)	Sample no.	Color
less than 150	271	2.5Y 5.5/2 (grayish brown)
	268	2.5Y 3.5/1 (very dark gray)
	235	2.5Y 3.5/1 (very dark gray)
	216	5Y 2.75/2 (very dark grayish brown)
	131	no specimens
	30	no specimens
	8	5Y 2.75/2 (very dark grayish brown)
200	3696	5Y 4/3 (olive)
200 to 350	3556	5Y 2.5/1 .5 (black)
	3511	2.5Y 2/1 (black)
	3375	2.5Y 2/1 (black)
	3320	2.5Y 2/1 (black)
	3230	2.5Y 2.5/0 (black)
	3072	2.5Y 2.5/0 (black)
	3020	2.5Y 2.5/0 (black)
350	2852	2.5Y 2.5/0 (black)
greater than 350	2689	2.5Y 3/0 (very dark gray)
	2550	2.5Y 3/0 (very dark gray)
	2415	2.5Y 3/0 (very dark gray)
	2336	2.5Y 3.5/0 (very dark gray) possibly recrystallized
	2161	no specimens

and less color saturated. The colors (grays, browns, blacks) are similar to those of some fossils (Table 7; Figures 1,*12*–1,*16*). In sediment from Bayou Desiard, ostracodes without soft parts first became redder, then yellower, then redder, but in all instances as T-P increased they became darker, with colors about equal to the dark reds, browns, and blacks characteristic of many fossil ostracodes. Freshwater ostracodes in pure calcite (a control) became slightly redder, then white (10YR 8/1), with little color saturation, showing none of the profound changes that took place with the bayou sediment (Table 7).

It is interesting to note that freshly collected, marine and freshwater algae as well as leaves and twigs of deciduous trees caused all shells to be destroyed at temperatures and pressures greater than or equal to 120°C and 400 atm.; that is, there was no recovery of the shells placed in the vessels with these organic materials. The sediment from Bayou Desiard obviously included organic material already altered; the gross organic structures were not identifiable at a magnification of 100X. It was not nearly as destructive to the calcareous shells as was the fresh organic material.

As indicated in Table 8, tests demonstrated that crude oil can be a coloring agent. Over time, from 24 to 432 hours, at one atm. and 50°C in crude oil (API 46°), marine specimens in quartz and oil became redder, darker, and more color saturated. They changed progressively to olive yellow to light olive brown to brown. In calcite and oil, shells became redder and darker, then dark yellowish brown. In Elf clay and oil, shells became redder and darker, becoming light olive brown, pale brown, and light brown. Again, these colors are common among fossil ostracodes. The shells treated in crude oil at atmospheric pressure at 50°C were then aged at room temperature and pressure for an additional 2,880 hours, which caused no further changes in color.

Specimens heated with quartz and crude oil at higher temperatures (and still at atmospheric pressure) first became redder, darker, and more color saturated and then became lighter and less color saturated above 371°C. Those heated in calcite and Elf clay showed little change in value, but they lost color saturation (chroma) at higher temperatures (Table 9; Figures 1,*1*–1,*9*).

Shells heated in calcite and crude oil at elevated temperature and elevated pressure became darker, and more color saturated up to about 210°C, 700 atm.; at higher T-P shells retained the same hue, but became lighter and had lower color saturation (Table 10). In quartz and oil, specimens became redder and even darker than in calcite and then lost color saturation (chroma) at about 300°C, 1000 atm. These colors, too, are similar to the colors of many fossil ostracodes and more or less simulate the downhole distribution of colors of specimens from some wells (see Tables 14–17).

As mentioned above, many ostracode fossils have colors similar to those resulting from heating in crude oil or organic-rich sediments. In a section of Early Cretaceous argillaceous rocks from the Yanguas-Arnedillo area of northeastern Spain (Table 11), approximate paleotemperatures were interpreted from metamorphic mineral

Table 12. Results of reheating (at atmospheric pressure) colored Cretaceous ostracode shells from sample 3320 of the Yanguas-Arnedillo section of northeastern Spain; color of fossils was 2.5Y 2/0 (black).

Temp. (°C)	Color
100	7.5YR 2.5/0 (very dark gray to black)
200	7.5YR 2/0 (black)
300 – 325	7.5YR 2/0 (black)
400 – 425	7.5YR 3/0 (very dark gray)
490 – 510	7.5YR 3.5/0 (very dark gray)
600 – 625	7.5YR 3.5/0 (very dark gray)
675 – 725	7.5YR 3.5/0 (very dark gray)
800	7.5YR 6.5/0 (light gray)
900	10YR 8/1 (white)

Table 13. Colors of Cretaceous ostracode shells after experimental reheating at atmospheric pressure. Shells were dark grayish brown (2.5Y 3.5/2) as recovered from 1650 to 1660 m (Barremian) in Elf-Agip Congo borehole BGM-1 (from Zaire).

Temp. (°C)	Color	Remarks
100	10YR 3/1 (very dark gray)	
200	7.5YR 3.5/0 (very dark gray)	
300 – 325	7.5YR 3.5/2 (dark brown)	
400 – 425	7.5YR 4.5/2 (dark brown)	
490 – 510	5YR 4.5/1 (dark gray)	
600 – 625	5Y 4.5/2 (dark reddish gray)	
700	7.5YR 6.5/1 (gray)	Flaky, cracked, has darker internal mold
800	7.5YR 6.5/1 (gray)	Cracked, frosty
900	7.5YR 8/0 (white)	Flaky, remnants do not effervesce in 5% HCl

suites; ostracode shells were differently colored from one temperature zone to another (Oertli, personal communication, 1984; Kontrovitz & De Hon, 1986). In the rocks interpreted as having been subjected to temperatures less than 150°C, shell color was in the range from 2.5Y 5.5/2 (grayish brown) to 5Y 2.75/2 (very dark grayish brown); at temperatures of about 200°C the shell color was 5Y 4/3 (olive). From about 200°C to less than 350°C colors were 5Y 2.5/1 to 2.5Y 2.5/0 (black). At about 350°C the color was 2.5Y 2.5/0 (black). Shells presumably subjected to temperatures higher than 350°C were slightly less color saturated (Table 11).

Some specimens from northeastern Spain that were reheated in the laboratory changed to new colors. For example, those from locality 3320, which were colored very dark gray to black (7.5YR 2.5/0), began to lighten at about 400°C (Table 12). Those from boreholes showed similar changes, as exemplified by shells from Cretaceous sediments from Zaire (Table 13). These shells were originally dark grayish brown (2.5Y 3.5/2); upon heating, they began to lighten at about 400°C, indicating that the coloring agent had been driven off by heat.

Fossil ostracodes from boreholes in Cretaceous rocks from Zaire, Gabon, and Senegal, have downhole differences of color similar to those produced in the laboratory experiments (Tables 14, 15, 16; Figures 1,*17*–1,*23*). Shells from boreholes in Mesozoic and early Tertiary sediments from the Fastnet basin and the southern region of the north Celtic Sea have colors that indicate thermal maturation (Table 17). "For the thirty-four wells studied, twenty-seven contained sufficient ostracod samples to form colour profiles . . . for each well. A summary of the alteration . . . illustrates that ostracod colour is largely independent of initial . . . lithology and is a product of subsequent thermal influences" (Ainsworth *et al.*, 1990). It should be noted that all fossils were readily soluble in 5 percent HCl, yielding an amorphous mass of organic material similar to that from modern forms (Sohn, 1958).

Igneous rocks and sulphide mineralization implying thermal activity were noted in some wells of the Irish and U. K. offshore areas. In the three wells with thick igneous intrusions, ostracode color and vitrinite reflectance show the strong influence of the sills that extends over a thickness that is three to four times that of the intrusion (Ainsworth et al., 1990; see Table 17).

The colors of nonpyritized fossil shells were unaffected after 336 hours in such common organic solvents as benzene, acetone, xylene, and ethyl alcohol. Those so treated and other nonpyritized fossils were all bleached to white or pale yellow when heated above 375 to 450°C, as indicated above. This fact and the result showing that modern ostracodes develop dark colors only when heated in an organic-rich substance tend to support the contention that they are darkly colored by extraneous, matured, organic materials. Upon heating, pyritized shells become reddish (weak red; 10R 4/4); thus they can be distinguished from those we interpret to be colored by organic compounds.

SUMMARY AND CONCLUSIONS

(1) Modern ostracode shells subjected to elevated temperatures and pressures change colors but never attain the dark colors seen in many fossils.

(2) Only shells treated in mature, extraneous, organic matter, including petroleum, develop the dark colors similar to those of many fossils.

Table 14. Ostracode colors from Neocomian to Barremian sediments in the Elf-Agip Congo borehole BGM-1 (from Zaire).

Depth (m)	Color	Remarks
1415 – 1440	5Y 7.5/2 (light gray)	?mold
1650 – 1660	10YR 4.5/2 (dark grayish brown)	?shell
1920 – 1940	10YR 6/2 (light brownish gray)	?shell
2060 – 2070	10YR 5.5/2 (grayish brown)	?mold
2125 – 2145	10YR 2/2 (very dark brown)	?mold
2200 – 2210	10YR 2/1 (black)	?mold
2455 – 2465	no specimens	——
3358 – 3368	5Y 2/1 (black)	?shell
3610 – 3620	5Y 2.5/1 (black)	?shell

? = probably

Table 15. Ostracode colors from Cretaceous sediments in the Shell-Gabon/Elf-Gabon CRM-1 borehole.

Depth (m)	Color	Remarks
2080 – 2100	2.5Y 4.5/2 (dark grayish brown)	probably mold
2300 – 2320	2.5Y 3.5/2 (very dark grayish brown)	shell
2525 – 2545	5Y 2.75/2 (black)	shell
2740 – 2750	10YR 5.5/3 (brown)	mold, mottled
3010 – 3020	5Y 5.5/3.5 (olive)	mold & shell
3288 – 3314	2.5Y 3.5/2 (very dark grayish brown)	probably shell
3618 – 3627	2.5Y 4.5/2 (dark grayish brown)	probably shell

Table 16. Ostracode colors from Neocomian, Coniacian, and Santonian sedimentary rocks from the Elf KAF-1 Senegal borehole.

Depth (m)	Color
1345	2.5Y 5.5/4 (light olive brown)
1945	5Y 4.5/2 (olive gray) (?ostracode)
2360	5Y 2/2.0 to 2.5Y 5/2 (black to olive gray)
2752	5Y 3/1 (very dark gray)
3340	5Y 2.5/2 to 5Y 3.5/2 (black to dark olive gray)
3730	5Y 2.5/2 to 5Y 3.5/2 (black to dark olive gray)
4120	5Y 2.5/1 to 5Y 3/2 (black to dark olive gray)
4528	5Y 3/1 to 5Y 3.5/2 (very dark gray to dark olive gray)
5020	5Y 2.5/1 (black)
5280	5Y 3.5/2 (dark olive gray)

Table 17. Colors of ostracode shells from the Gulf 56/18-1 well, northern Fastnet Basin, offshore Ireland (modified from Table 1 of Ainsworth, Burnett, & Kontrovitz, 1990).

Depth (m)	Color (mean)
1768	2.5 Y 8/4 to 10YR 8/4 (very pale yellow to very pale brown)
1813	2.5Y 8/4 to 10YR 8/4 (very pale yellow to very pale brown)
1908	2.5Y 8/4 to 10YR 6/6 (very pale yellow to brownish yellow)
1969	10YR 6/6 (brownish yellow)
2170	10YR 6/6 to 10YR 4/6 (brownish yellow to dark yellowish brown)
2201	10YR 4/6 (dark yellowish brown)
2274	10YR 4/6 to 5YR 3/4 (dark yellowish brown to dark reddish brown)
2441	10YR 4/6 to 10YR 2/1 (dark yellowish brown to black)
2727 to 2856	Thick basic sill
3005	*neutral 2/0 (black)
3155	2.5Y 3/2 to *neutral 2/0 (very dark gray black to black)
3243	10YR 4/6 to 5YR 5/6 (dark yellowish brown to dark reddish brown)
3272	Thin basic sill
3397	Thin basic sill
5593	10YR 4/6 to 5YR 5/6 (dark yellowish brown to dark reddish brown)

*for achromatic colors that have zero chroma and no hue (Munsell Soil Color Charts, 1988)

(3) Iron compounds other than pyrite cause only light and poorly saturated colors in ostracode shells.

(4) Highly colored ostracode shells mark areas near igneous rocks and in metamorphic rocks; colors are diagnostic of the level of thermal alteration.

(5) Fossil ostracodes from some boreholes have downhole color differences similar to those obtained experimentally.

(6) Darkly colored fossils reheated in the laboratory undergo new color changes; they begin to lighten markedly at about 375 to 400°C, eventually becoming pale yellow or white, thereby indicating that organic compounds caused the coloration (Gross, 1971).

(7) Upon heating, pyritized shells become reddish (weak red; 10R 4/4); thus they can be distinguished from those colored by organic compounds, which whiten upon heating.

(8) The dark colors of fossils are different (hue, value, chroma) in different thermal zones, and ostracode color appears to be broadly diagnostic of thermal history.

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