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BIT-METAMORPHISM, ILLUSTRATED BY LITHOLOGICAL DATA FROM GERMAN NORTH SEA WELLS[1]

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ABSTRACT

Taylor, J. C. M. 1983 Bit-metamorphism, illustrated by lithological data from German North Sea wells. In: J. P. H. Kaasschieter & T. J. A. Reijers (eds.): Petroleum geology of the southeastern North Sea and the adjacent onshore areas (The Hague, 1982) – Geol. Mijnbouw 62: 211-219.

Permo-Carboniferous redbeds encountered in some deep German North Sea wells are commonly altered when drilled with diamond bits. The process has been referred to as 'bit-metamorphism' by well-site geologists and others. Severely altered cuttings constitute over 80% of samples; they are hard, and when oil-based muds have been used are almost black and generally magnetic.

Study of cuttings using petrographic, X-ray and chemical methods, supplemented by scanning electron microscopy, demonstrates that the process involves the reduction of particle size by shearing, followed by cementing or welding of the particles into a matrix superficially resembling a glass. The bulk chemical analysis of strongly altered cuttings is similar to that of accompanying unaltered material, though slightly richer in silica, but X-ray reflections of all minerals except quartz and feldspar are reduced or lost. All rock types are believed to be affected, but abundance of quartz and accompanying above-average hardness probably favour the process. Oil-based muds are not thought to be a necessary factor, but when used their breakdown may give rise to spurious gas readings.

It is not certain whether the altered cuttings are bound together by precipitation of colloidal silica or by fusion to a glass. Further research is needed and might be expected to lead to better cuttings, reduced drilling torque, and less bit wear.

INTRODUCTION

The occurrence of black vitreous material in ditch cuttings from the Permo-Carboniferous redbed sequence below the 'Rotliegend Salinar', when drilled with diamond bits and oil-based muds, was noted by well-site geologists working in the German sector of the North Sea in the late 1970's. The material appeared in the 'Rotliegend Tonstein', became common in the 'Welchelfolge', and locally very abundant in the Rotliegend Basal Sandstone and below, comprising 80% or more of some samples. Because both volcanic rocks and coals were considered to be possible in the section, the presence of this dark shiny material caused some initial confusion, but it was soon recognised that it was an artefact of the drilling process, and the term 'bit-metamorphism' was aptly coined. This name has been retained in the present paper.

In 1978 V. C. Illing & Partners were commissioned by Union Texas Germany Inc., operators for the J/13 block, to attempt to identify the cause of this phenomenon, using samples from J/13-1 and J/13-2, and from the adjacent Placid J/16-1 and Deutsche Erdöl AG B-2 in block H/15. The location of these wells is given on figure 1, and the generalised stratigraphy of the relevant section in Table I.

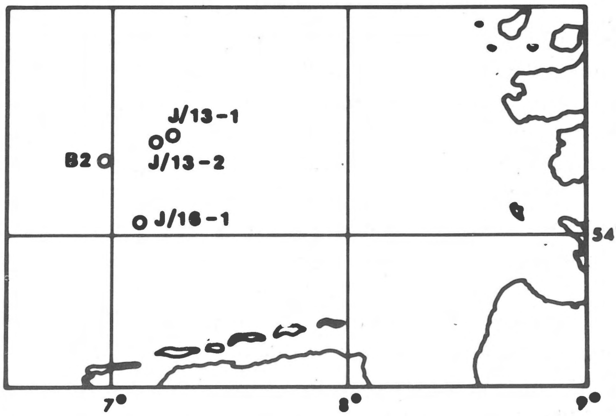

Fig. 1
Location of wells used in study.

Following petrological examination and wireline log interpretation by the writer, selected samples were submitted to

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[1] Manuscript received: 1982-11-27.

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Table I
Summary of Permo-Carboniferous redbed sequence in offshore area of Northwest German Basin, with formation names in common use.

SYSTEM	STAGE OR GROUP		UNIT	DOMINANT LITHOLOGY
PERMIAN	ROTLIEGENDES	UPPER	HASELGEBIRGE SALINAR	Halite and red mudstone
			TONSTEIN	Red mudstone and siltstone, minor anhydrite
		MIDDLE	WECHSELFOLGE	Thin alternations of reddish mudstone, siltstone, sandstone and limestone
			SANDSTEIN OR BASAL SANDSTONE	Sandstone, conglomerate
CARBONIFEROUS	? STEPHANIAN			Reddish sandstone, siltstone, shale, with local conglomerate and thin limestone

more extensive tests: XRD determination, SEM photographs and chemical analyses were carried out at Imperial College, London, and further XRD analyses performed at Cambridge University.

There are indications that the process is now being recognised more widely, and more companies are encountering difficulties in interpreting cutting samples produced during drilling with diamond bits. Although oil-based mud appears to be responsible for the blackening, most of the other attributes of bit-metamorphism are recognisable in cuttings where oil was not used. As just one example from another area and a different stratigraphic interval, white powdery material and friable aggregates are commonly returned when drilling the Middle Jurassic sands in parts of the East Shetland Basin, UK North Sea, having been variously described by mud-loggers as 'kaolin', 'gypsum', or 'anhydrite'. Although this material has not been studied exhaustively, XRD analyses carried out for the writer failed to detect minerals other than quartz and feldspar; its appearance in thin section closely resembles that of samples described in the present paper.

Despite the widespread occurrence of the problem, we are not aware that a thorough investigation has previously been published. It is hoped that the results presented here will help others in the correct interpretation of altered cuttings, and stimulate further research.

DESCRIPTION OF ALTERED CUTTINGS

Fig. 2
Untreated cuttings from an interval of silty shale and sandstone showing various degrees of alteration. Well J/13-2, 4711 m (see Table II for analyses, also Figs. 9b and 11). Note characteristic scoriaceous surfaces. Cuttings average about 1 mm long.

Altered cuttings are most obvious when they are dark, hard and, as is commonly the case, magnetic. Such cuttings occur in J/13-1, J/13-2 and J/16-1 (all drilled with oil-based muds), both as persistent minor amounts accompanying normal cuttings over extensive intervals of 50 m or more, and as a dominant constituent (up to 80 or 90% of samples) through intervals of a few tens of meters at a time. The major occurrences are commonest in the Rotliegend Basal Sandstone and older strata. A typical mixed sample of ditch cuttings, untreated except for washing, is shown in figure 2.

Under the binocular microscope the altered cuttings generally have a rough knobbly surface and dark grey to black colour. They are hard enough to scratch a steel needle, and break with a conchoidal or sub-conchoidal fracture, commonly revealing a faintly banded structure paralleling the longest axis of the cutting. The broken surfaces have a vitreous to resinous lustre which becomes duller after removal of oil by solvents. The larger and more elongated pieces (up to 2 – 3 mm long) tend to have a characteristic and probably significant shape. They are slightly curved along the long axis; the convex side is rough, but the concave side is smoother and sometimes longitudinally striated. Transverse sections tend to be airfoilshaped. Imbricate cuttings as much as 15 mm long have been reported (F. GETZ, pers.com.). Thus, they are not unlike the curly swarf cut by an edge tool from metal, and appear to have passed through a ductile or brittle phase before reaching their present condition. A selection of enlarged views is illustrated in figures 3 and 4.

Such material is resistant to common laboratory reagents. It is not softened by standing for several days in water, is unaffected by organic solvents or concentrated hydrogen peroxide, and does not adsorb organic dyes, such as toluidine blue, strongly. It does not effervesce with cold or hot concentrated hydrochloric acid, but yields a yellow-green leachate containing both ferrous and ferric iron with the latter. Many cuttings are sufficiently magnetic to attach themselves to a strong permanent magnet.

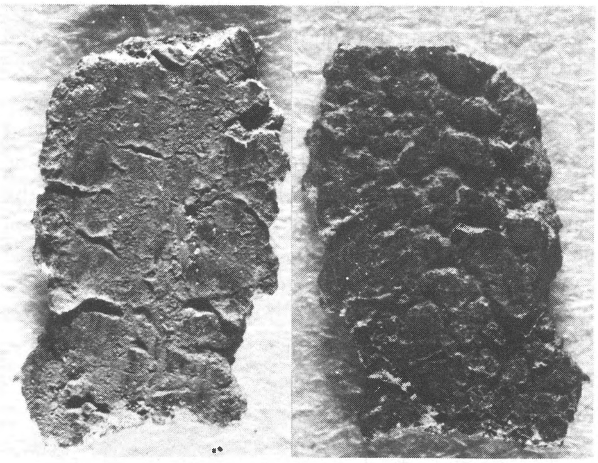

Fig. 3 a, b
Two sides of a hard black altered cutting about 4 mm long; one relatively smooth and flat (a) with faint longitudinal tool marks and deep crevasses, the other (b) more rounded and knobbly. From sandy interval at 4990 m in well J/13-1 (see Table II for analyses, Fig. 7 for photomicrograph, and Fig. 9a for SEM).

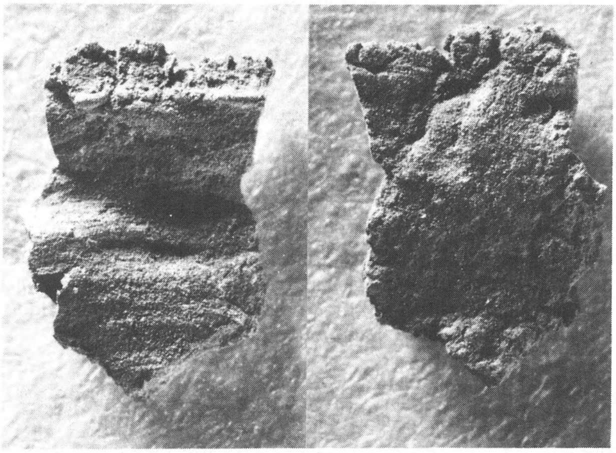

Fig. 4 a, b
Two sides of a broken grey hard altered cutting 2 mm long. Note brittle fracture (sides), crenulate edge (top), grooved surface on one side (a) and knobbly convex reverse side (b). From 4721 m in well J/16-1; drilled lithology sandstone and minor shale.

When samples are examined under the binocular microscope the distinctive appearance of the 'vitreous' black cuttings just described – which are believed to represent the more extreme stages of bit-metamorphism – tends to distract attention from more subtle indications of alteration present amongst the other cuttings. Thus absence of lamination, poor cohesion, rounding of edges, and distortion is common in many argillaceous cuttings and is often attributed by loggers to soft lithology (claystone rather than shale). In fact this origin is not very plausible in formations of the age under discussion (Middle Permian to Late Carboniferous) and depth of burial (present depth about 4250 m), which also show relatively high sonic velocity (about 3960 m/sec.). It is more likely that the present properties are the result of crushing during drilling, believed to represent incipient bit-metamorphism, and that the lithology in situ was relatively hard.

Significantly, cuttings apparently composed of mudstone can be found exhibiting a transition from normal red-brown colour on one side to grey on the other; the grey side usually being the harder. Another key piece of evidence is provided by many of the cuttings from the Wechselfolge and deeper in B-2, which show characteristic distortion and hardening without blackening; this well was drilled with salt-bentonite mud, not oil-based mud.

THIN SECTION APPEARANCE

The effects of bit-metamorphism, especially in its incipient phases, are much more noticeable in petrographic thin sections than under the binocular microscope, which helps to explain why the phenomenon has not been more extensively reported. Sections made from hand-picked vitreous black material show a wide variety of textures and fabrics, but the following features are invariably present: – colours by transmitted light ranging from pale gold through reddish brown black; – streaks of dark carbonaceous, argillaceous, or hematitic material; – flow-banding or zones of different colour or texture; – greater or lesser numbers of floating unsorted quartz and feldspar grains, usually rounded, often fractured; – a groundmass of progressively finer particles of quartz and feldspar passing down below the limits of resolution and embedded in isotropic glass-like material with a refractive index lower than quartz. Similar textures and fabrics but generally paler colours are found in cuttings sectioned from siliceous altered material in B-2, drilled without oil.

Thin sections cut from random as opposed to hand-picked cuttings show intermediate stages of alteration leading up to the extreme forms just described. They also show that all rock types are affected, and that there is a certain amount of convergence in the later stages. Early and intermediate stages of alteration of siltstone/silty mudstone are illustrated in figure 5. Alteration starts by simple mechanical distortion of bedding laminae accompanied by loss of orientation of elongated grains; the appearance is difficult to differentiate objectively from various possible forms of synsedimentary disturbance. More advanced alteration is marked by comminution of sand and silt grains and either homogenisation (Fig. 6) or development of a strongly laminated structure. These changes are commonly accompanied by loss of red-brown colour and substitution of paler golden and darker greyish tints, usually with reduction of birefringence in the matrix.

Sandstones show fracturing, rotation, and rounding of grains, fracturing of cement and flow of matrix, loss of grain boundaries, and mixing of the components. Polarisation colours diminish as particle size becomes finer, leading eventually to the isotropic glassy appearance that characterises advanced alteration (Fig. 7).

Weathered spilite, which occurs locally in conglomeratic beds in the region, develops contrasting laminae of hematite and comminuted feldspar, the latter developing, like quartz, a golden colour and loss of birefringence. Limestones and carbonate cements show shearing and reduction of crystal size, finally approaching a uniform pasty cryptocrystalline texture of light brown colour by transmitted light, retaining high-order aggregate polarisation under crossed polars.

NATURE OF IN-SITU LITHOLOGY

The petrographic evidence suggests that bit-metamorphosed cuttings are not the product of any single rock type. Further evidence is provided by the wireline logs. Examples from all four wells are given below:

B-2 – Thin sections of cuttings from 4155 m, 4291 m (see Figs. 5, 6), 4358 m and 4485 m all show prominent reconstitution, including the presence of glass-like material. Wireline logs show the first example (Rotliegend Tonstein) to come from thinly interbedded siltstones and shales; the second (Fig. 8) and third (Rotliegend Wechselfolge) from similar or slightly sandier intervals (with the possibility of thin limestone incorporated in the sample at 4291 m); the fourth (Rotliegend Sandstein) consists of cemented sandstone.

J/16-1 – The first high concentration of hard black cuttings occurred at about 4304 m in the Rotliegend Tonstein, a level shown by the wireline logs to consist of normal shale, possibly silty. A second major concentration occurs at 4563 m in conglomeratic sandstones of the Rotliegend Basal Sandstone. Other concentrations occur at 4663 m and 4770 m in thinly interbedded silty or sandy shales with some limestone bands, at 4724 m and a few meters above (Figs. 4, 8; Table II), and 4849 m is cemented sandstones.

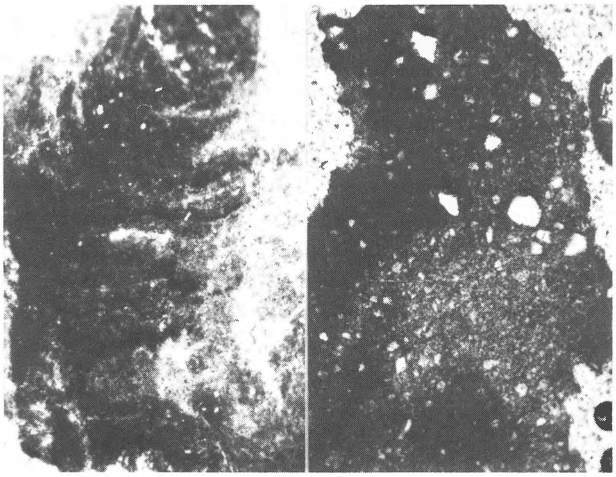

Fig. 5 a, b
Thin sections in plane polarised light from 4291 m in well B-2; height of field 1 mm. (a) Deformed mudstone cutting showing banding and shear planes. (b) Deformed cutting of argillaceous sandy siltstone showing partial transformation of matrix. Dark cloudy areas to the left retain hematite pigmentation and clay polarisation tints. Gray mottled area in centre and right has lost red colour and is almost isotropic. White grains are quartz.

J/13-1 – Hard, black material became dominant in cuttings at about 4910 m (Rotliegend Wechselfolge) where the wireline logs indicate silty shale. A similar lithology is indicated by the logs at 4930 m (sample analysed – see Table II). At 4990 m (Table II; Figs. 3, 7, 8, 9a) the logs indicate sandstone, and at 5040 m (Table II) interbedded shale and sandstone.

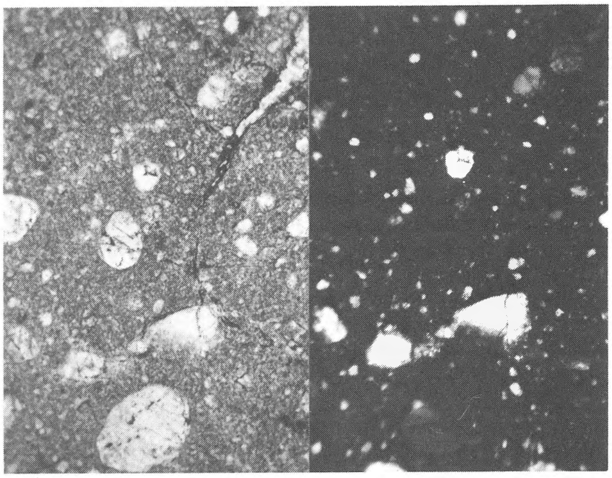

Fig. 6 a, b
Thin section of strongly altered hard grey cutting, believed to have been sandstone originally, from well B-2, 4291 m; height of field 1 mm. (a) plane polarised light; (b) crossed polars. Notice rounding of surviving sand grains (mostly quartz), and reduction of groundmass by milling to an almost isotropic medium which nevertheless became cohesive enough for the late crack visible on the right of the field to propagate through rather than around quartz grains.

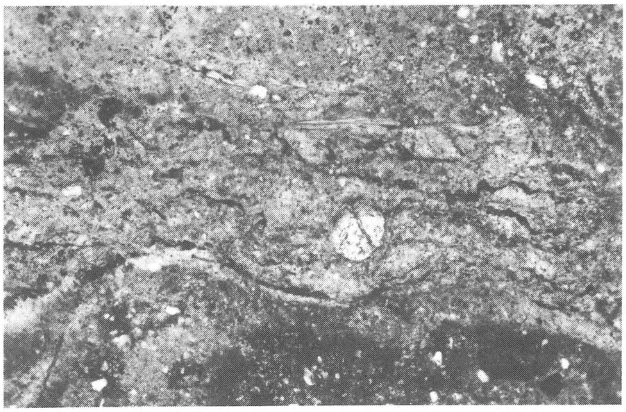

Fig. 7
Thin section of hard grey cutting from well J/13-1, 4990 m, in plane polarised light; width of field 1 mm. This shows an advanced stage of bit-metamorphism. The original lithology was probably a sandstone with argillaceous and silty layers (see also Fig. 3, and Table II). Apart from rare surviving quartz sand grains (e.g., centre, white) the rock has been reduced to a streaky, flow-banded glass-like material, gold by transmitted light, and almost totally isotropic. Clay, hematite, and carbonaceous matter form the dark streaks.

J/13-2 – Although cutting quality was generally better in J/13-2 than in J/13-1 and J/16-1, hard black material again appeared in the Rotliegend Tonstein, becoming abundant at about 4500 m where the wireline logs indicate shale with thin alternations of sandstone and siltstone, not markedly different from the section above. Black material was common around 4600 m in the Wechselfolge where the logs show slightly thicker alternations of shale and siltstone or sandstone, and became dominant at 4660 m in apparently similar or slightly sandier lithology in the Rotliegend Upper Basal Sandstone (see analysis in Table II). Another marked concentration occurred in samples below 4700 m in the Lower Basal Sandstone, shown by the wireline logs to be cemented sandstone. The sample analysed at 4711 m (Table II; Figs. 2, 9b, 10, 11) came from a somewhat siltier and shalier sandy interval.

It is clear from the above that no unique lithology is

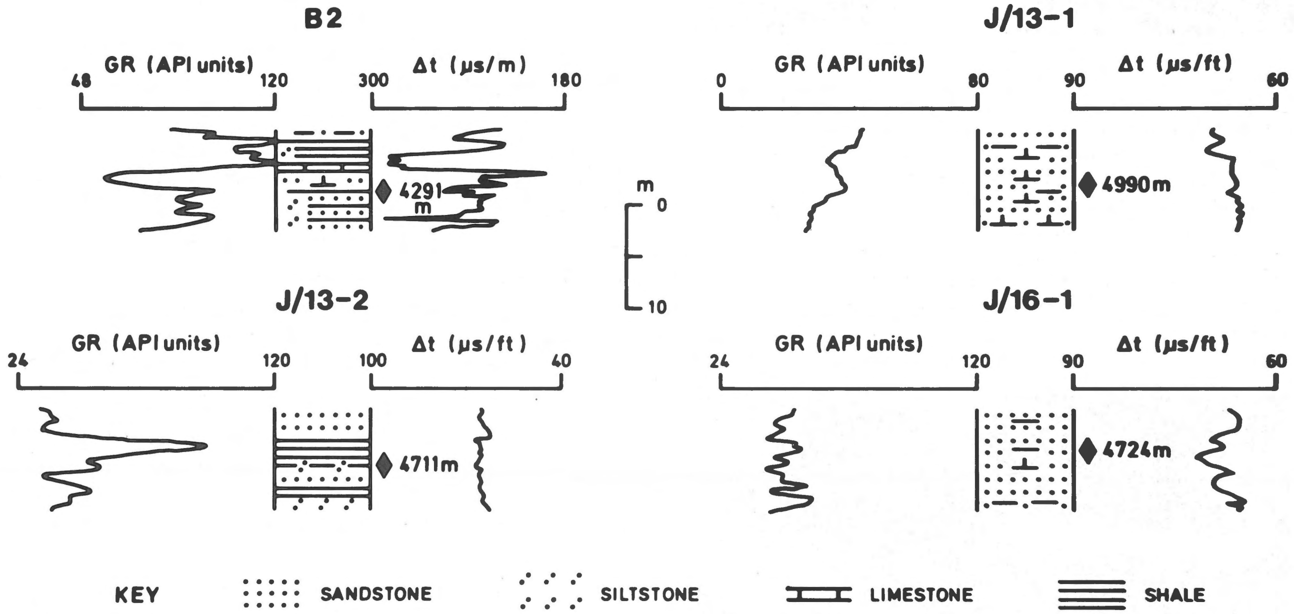

Fig. 8
Examples of logs summarising lithology in intervals where altered cuttings were abundant. Depths indicate samples with analytical data (Table II) or illustrations in this paper.

Table II
Combined analytical data, comparing results on altered and unaltered cuttings. See Text for methods used and significance.

WELL	SAMPLE m	DESCRIPTION OF CUTTINGS	FORMATION	LITHOLOGY ACCORDING TO SCHLUMBERGER LOGS	X-RAY ANALYSIS										CHEMICAL ANALYSIS									
					NON CLAY FRACTION %								Clay Fraction %		% W/W OF SAMPLE AS RECEIVED									
					QTZ.	FELD.	CALC.	DOL.	ANHY.	HEM.	MAG.	OTHER	MIC.	CHLOR.	SiO_2	K	Na	Ca	Mg	Al	Fe	SO_4	CO_3	loss on ignition (500°C)
J/13-1	4930 A	RED SOFT SILTY MUDSTONE	WECHSELFOLGE	SHALE WITH THIN SILTSTONES AND SANDSTONES	35	27	8	3	3	14	–	Halite 10	88	12	not analysed									
	4930 B	BLACK, HARD MATERIAL			57	28	5	8	–	–	–	Halite 2	Quartz only											
	4990 A	RED SOFT SILTY MUDSTONE	BASAL SANDSTONE	SANDSTONE	not analysed								84	16	not recorded	1·3	4·9	4·2	0·92	4·9	3·8	not determined		
	4990 B	BLACK NON-MAGN.			94	6	–	–	–	?	–	unidentified <5	Quartz only		not recorded	0·23	1·7	1·8	0·15	1·8	1·2	not determined		
	4990 C	BLACK MAGNETIC													not recorded	1·1	1·8	2·8	0·62	4·6	3·4	not determined		
	5040 A	LIGHT RED-BROWN MUDSTONE	BASAL SANDSTONE	SHALE AND SANDSTONE	36	26	9	–	3	13	–	Halite 13	84	16	not analysed									
	5040 B	BLACK, HARD MATERIAL			61$^{\%.}$	34	5	–	–	trace	–	–	Quartz only											
J/13-2	4660 A*	RED FRIABLE SILTY MUDSTONE	BASAL-SANDSTONE	THIN BEDS OF SHALE AND SANDSTONE	58	17	8	–	17	present	–	–	75	25	60·6	3·0	1·5	3·4	2·0	8·2	4·4	2·7	<0·2	9·9
	4660 B*	BLACK MAGNETIC			89	11	–	–	–	–	possible	–	present	–	79·3	2·4	1·5	1·0	1·2	7·7	4·5	1·2	<0·2	3·3
	4711 A*	RED-BROWN SOFT MUDSTONE	BASAL SANDSTONE	SILTY SHALE AND SANDSTONE	53	14	7	–	13	present	–	Halite 13	80	20	70·7	2·2	2·1	3·1	1·4	5·8	2·9	3·1	0·2	7·4
	4711 B*	BLACK MAGNETIC			90	10	–	–	–	–	–	–	present	–	71·8**	1·5	1·5	1·2	0·53	5·6	3·0	2·8	<0·2	3·4
J/16-1	4724 A	RED-BROWN SOFT MUDSTONE	? STEPHANIAN	QUARTZ-CEMENTED SANDSTONE	53	40	3	–	–	5	–	Barite trace	80	20	not recorded	1·3	1·2	2·4	0·62	5·4	3·1	not determined		
	4724 B	BLACK, HARD MATL.			not analysed								na	na	not recorded	1·2	1·3	1·4	0·63	4·9	3·9	not determined		

Abbreviations:

na	not analysed	QTZ.	quartz	FELD.	feldspar
DOL.	dolomite	ANHY.	anhydrite	HEM.	hematite
MIC.	mica (illite)	CHLOR	chlorite	MAGN.	magnetic
CALC.	calcite	MAG.	magnetite	MATL.	material

Footnotes: *Sample analysed by Dr. H. Shaw, London; chlorite and kaolinite undifferentiated, quoted here as chlorite (remainder analysed by Dr. C. V. Jeans, Cambridge, kaolinite not detected); ** Result believed to be low due to incomplete attack by reagents;

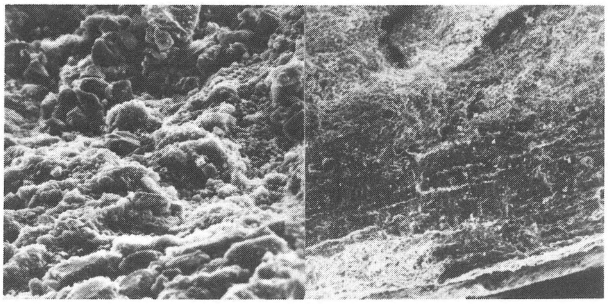

Fig. 9 a, b
SEMs (see Table II for analyses). (a) Broken surface of hard black material in relatively early stages of reconstitution from sandstone. Heterogeneous assortment of fractured and abraded quartz grains, with traces of streaky texture in lower part where they are locally merged together. Width of field 0.14 mm. From well J/13-1, 4990 m. (b) General view of streaky fractured surface of black cutting representing more advanced stage of alteration; (see Figs. 10a, b and 11b for close-ups). Simultaneous X-ray reveals silicon, iron, calcium, potassium and titanium. Width of field 0.6 mm. From well J/13-2, 4711 m.

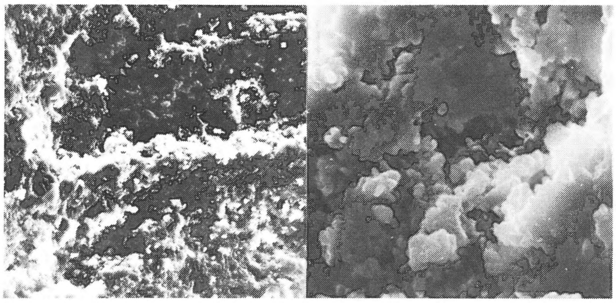

Fig. 10 a, b
SEMs (see Table II for analyses). (a) Enlarged portion of Fig. 9b, showing that streaks are due to layers of contrasting porosity and degree of coalescence. Width of field 0.1 mm. (b) Further enlargement showing that hard streaks are formed by merging of small grains. Simultaneous X-ray analysis shows only silicon. Note absence of overtly crystalline phases. Width of field 12.5 µm.

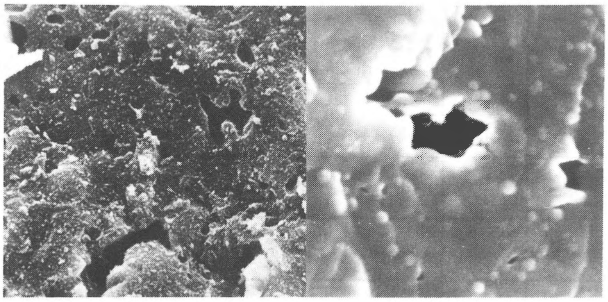

Fig. 11 a, b
(a) Another cutting from 4711 m in well J/13-2, showing more advanced coalescence of particles, leaving scattered rounded pores. Width of field 19 µm. (b) Maximum available enlargement of sample seen in Fig. 9b and Fig. 10. Surface of coalesced area is composed of sub-spherical protuberances. These resemble published pictures of colloidal silica particles (GREER, 1971; JEANS, 1978). Width of field 2.8 µm.

necessary to enable alteration to take place during drilling. Combinations of shale and silt or sand seem to be the commonest raw materials. Opinions of wellsite geologists appear to differ somewhat in the matter, some regarding silt content as a significant factor, others favouring the importance of sand, perhaps in some instances in layers too thin for wireline-log detection.

X-RAY ANALYSIS

Because of the petrographic evidence for progressive change from normal lithologies to vitreous material, the next logical step in the investigation was to compare the mineralogy of unaltered and altered cuttings, using X-ray diffraction methods. There is a fundamental problem in making such a comparison using ditch cuttings, in that, because of the possibility of caving, there can be no absolute guarantee that any two pieces were derived from the same interval. In the wells studied, however, hole conditions were generally excellent, and cutting lithologies (with the exception of the altered material itself) closely followed the changes indicated by the wireline logs. The comparison was therefore considered to be worth attempting.

In ditch samples where the hard black products of bit-metamorphism are present, the bulk of the remainder generally appears to consist of silty red-brown mudstone, claystone or shale – which may, however, be partly altered or reconstituted, incorporating other lithologies. This preponderance of argillaceous reddish material is due to the tendency for siltstone and sandstone to be broken down and returned as individual grains, usually diluted by circulated material, and also to the comparative rarity and thinness of beds of limestone and other rock types in the stratigraphic section under consideration.

Consequently, samples are readily separated into two fractions on the basis of colour. In many cases the difference in magnetic properties can also be used. Hard black material was separated in this way from accompanying red cuttings in five ditch samples, and the two fractions were subjected to X-ray diffraction analysis – both for non-clay and clay minerals – using standard techniques. The results (Table II) present a strikingly consistent pattern, allowing for different analysts and equipment, and material from different formations in different wells. The non-clay fraction of the red material consists of about 45% quartz and 25% feldspar, with on average less than 10% each of carbonates, anhydrite, and hematite. Clay minerals are abundant, consisting of about 80% mica and 20% chlorite. This analysis is consistent with the petrographic character of the average redbeds encountered. In contrast, the black material consists almost entirely of quartz (averaging nearly 80%) and feldspar (nearly 20%).

In view of the magnetic properties of the black material, one analyst (Dr. H. Shaw) was instructed to search specifically for metallic iron and magnetite. No iron was found, but after changing from copper to cobalt radiation, the possible presence of magnetite was reported in one sample only (J/13-2, 4660 m B).

CHEMICAL ANALYSIS

The foregoing results indicate that hard black material is produced when drilling a normal sedimentary redbed sequence, and that it has a much simpler X-ray mineralogy than the average unaltered or partially altered material accompanying it. However, X-ray diffraction only detects crystalline phases, so that several alternative interpretations are possible:

1) The black material may consist only of minerals detected by X-ray (dominantly quartz and feldspar). Then either a) the bit might have reacted only with units of a particular lithology (by inference groups of quartz-cemented sand grains) to produce hard black material, leaving other components unchanged (only physical alteration would be necessary in this hypothesis); or b) bit-metamorphism may take as its raw material the mixed assemblage of the average redbed, and bring about physical or chemical changes which result in recrystallisation accompanied by loss of solid components other than quartz and feldspar.

2) The black material may consist of crystalline quartz and feldspar accompanied by non-crystalline disordered colloidal, or glassy phases. In this case a mixed assemblage might again be the raw material, but only physical processes would be necessary to bring about the change.

To resolve these alternatives chemical analyses were run on black and red fractions from one ditch sample in J/13-1, two from J/13-2, and one from J/16-1. Careful sample preparation was carried out using a combination of magnetic separation and hand-picking under the binocular microscope. The efficiency of the separation was estimated to be better than 98%. Principal metallic elements were determined by the Plasma Arc method. This is a rapid inexpensive technique that requires little material; no important cations are likely to be missed, but results are only approximate. Sulphate, carbonate, and loss on ignition were determined by standard methods. Problems were encountered with the silica determination using the Plasma Arc method and low values of 22-25% (not tabulated) were obtained on all samples, even when repeated. The cause is not fully understood. The tabulated silica figures on J/13-2 4660 m A and B and 4711 m A and B were subsequently obtained by an independent method: the samples were fused with lithium metaborate, dissolved in nitric acid, and determined by atomic absorption. Estimated precision on these determinations is not better than 5%, and the silica figure for 4711 m B is believed to be low due to incomplete attack. However, the tabulated figures for all these four samples now total between 90 and 102%, which is considered satisfactory for the methods employed.

The results given in Table II show that, within the limits of experimental error, the composition of the black (altered) and red (less-altered) material is similar throughout. The 'A' analyses are compatible with the petrography and X-ray data of typical unaltered red-bed cuttings, namely silty or sandy hematitic clay rocks with variable accessory amounts of calcite, dolomite, and anhydrite, with possible salt contamination from the drilling fluid. The 'B' analyses show somewhat greater amounts of silica, accompanied by slightly lower amounts of almost all other components. The amounts of metallic ions present are nevertheless still very high in view of the failure of X-ray determinations to detect minerals other than quartz and feldspar. This strongly suggests that the metals are present in hard black material in non-crystalline, e.g. glassy or colloidal form. It also suggests that the raw material for hard black material is only marginally different (slightly more siliceous) than that involved in producing normal or only partly altered cuttings.

The analyst reported that the black samples contained a small amount (not more than 1 - 2%) of material insoluble in HF which was not present when the samples were treated with a mixture of HF, HNO_3 and $HClO_4$, indicating that it was probably organic in nature. The material consisted of very finely divided black particles. We surmise that this was carbonaceous material derived from the oil-based drilling mud and that it was responsible for much if not all the dark colour of the bit-metamorphosed cuttings in J/16-1, J/13-1 and J/13-2. Iron was thought not to be in the form of magnetite, a view which conflicts with the scanty X-ray and SEM evidence on this point and leaves the problem of the magnetic properties unresolved. The only minor elements found (not tabulated) were barium and titanium, each present to less than 1%.

SCANNING ELECTRON MICROGRAPHS

Five samples of hard black material from J/13-1 and J/13-2 were examined under the scanning electron microscope in an attempt to discover the mechanism involved in alteration. Samples were prepared by gold-coating freshly broken surfaces. A selection of fields is illustrated in figures 9-11.

At magnifications of up to a few hundred times (Fig. 9) the views confirm the chaotic finely particulate texture deduced from thin sections. They also show the development of streaky structure to be due to alternating areas of greater and lesser porosity. At higher magnifications (Figs. 10 and 11a) it becomes clearer that dense areas are formed by coalescence of individual particles into what at first appear to be amorphous masses enclosing rounded pores. No crystal outlines are visible. At the highest available magnification (Fig. 11b) the surfaces are seen to be covered with small rounded protuberances resembling published pictures of colloidal silica (GREER, 1971; JEANS, 1978).

In the larger fields, simultaneous X-ray analysis detected silicon as the major component, accompanied by iron, calcium, potassium, aluminium, and in a few cases barium, in reasonable agreement with the bulk chemical analysis. In the restricted fields confined to the hard streaks only silicon could be detected. Dr. Grant considered that the spectra showing iron could possibly represent iron oxide (magnetite) coatings on silica grains.

DISCUSSION OF RESULTS

Examination of hard vitreous black cuttings under the binocular microscope and in thin section, supplemented by X-ray and chemical analysis and scanning electron microscopy, demonstrates that they were produced from the normal Permo-Carboniferous redbed sequence during drilling by predominantly physical processes, thus justifying use of the term 'bit-metamorphism'. If there is anything distinctive about the lithology which tends to be altered in this way, it is probable that it is more siliceous (for instance sandier or siltier) and harder than average. Whether there are other causative factors remains to be seen; the number of detailed observations does not yet adequately match the number of possible variables. For instance, the apparent increase in bit-metamorphism with depth might be related to the recorded downward increase in clastic quartz. On the other hand, the temperature of the hole may play a part; there are suggestions of a downward increase in temperature gradient in B-2 at about the level of the top of the Wechselfolge, where the mud temperature was approximately 111°C.

Two main processes are involved in bit-metamorphism. The first is reduction of particle size accompanied either by homogenisation or development of lamination, and is the result of powerful shearing action. The second is the cementing or welding of the particles together. The mechanism concerned in the second process is not finally resolved. There seem to be two possibilities. One is that at the high temperatures produced by shearing a significant amount of silica passes into colloidal solution from the finely ground quartz and silicates present, and that this re-precipitates as silical gel in the cooler regions away from the cutting edges. This explanation accords with the morphology of surfaces seen at very high magnifications under the electron microscope. It is not known, however, whether the dynamics of solution and re-precipitation are sufficiently rapid for it to take place in the time available.

Another possibility is that local fusion occurs. This is not a new idea. HARKER (1939) quotes a statement by BOWEN & AUROUSSEAU dating from as long ago as 1923 that 'even sedimentary rocks may be locally fused in the driving of a borehole'. Recent interest in the mechanism of faulting has also produced some relevant information. Calculations have shown that frictional heating on fault planes can produce temperatures in the region of 1500°C, sufficiently high to account for the formation of glasses (MCKENZIE & BRUNE, 1972), and the presence of glass has been demonstrated by FRIEDMAN ET AL. (1974) in artificial fault gouge formed by sliding sandstone surfaces over one another under pressure in the laboratory at ambient room temperature. Photomicrographs reproduced by FRIEDMAN ET AL. (1974; Fig. 1e, f) bear a strong resemblance to figure 6 in this report.

The main part played by oil-based drilling mud appears to be that of contributing the colour to altered cuttings, principally in the form of carbonaceous matter. If diesel oil in the mud is being carbonised by frictional heating, as suggested, corresponding generation of lighter hydrocarbons might be expected. In fact, according to J.R. GERNECK (pers. com.) abundant black cuttings are commonly accompanied by a proportional amount of ditch gas, with above-background readings of C_1 and especially C_{2+} hydrocarbons. The writer speculates that hydrocarbons may also be involved in chemically reducing hematite to magnetite; the analyses give slight support to this idea, but are not sufficiently sensitive to confirm it. The problem of the magnetic properties of the cuttings is complicated by the presence of fine steel junk in many ditch samples; it is particularly abundant in J/13-2. Free particles of steel were rigorously excluded from the analysed samples by hand-picking and by using a weak magnet before and after separating the red and black fractions (as weak magnet removes the steel without attracting the black cuttings).

Finely ground metallic steel may, however, have been incorporated into the black material, although it could not be detected in the X-ray analysis. One sample of hard black material separated into magnetic and non-magnetic fractions (J/13-1, 4990 m C and B, Table II) showed significantly more iron, aluminium, magnesium, and possibly calcium in the former on chemical analysis. This might be an indication of a reaction involving the formation of a metallic silicate.

It has been assumed so far that the alteration takes place at the interface between the bit and the rock being drilled – presumably at the contact point where the diamonds of the bit create the highest local pressures and shear stresses. It should be borne in mind, however, that the present evidence does not seem to exclude the possibility that it mights occur at other parts of the drilling string where high rubbing pressures occur. It may be relevant that in J/13-2, for example, the persistent steel contamination in the samples is believed to have derived from wear between the casing shoe and the drill pipe. On the other hand, the characteristic shape of the altered cuttings favours generation by the bit.

It is felt that this work confirms beyond reasonable doubt that formations can be profoundly altered during drilling with diamond bits. The results justify further research to help clarify the processes. This might involve controlled experiments to simulate borehole conditions. Further observations are also needed in the field and laboratory to pinpoint the factors – whether bit design, drilling weight or speed, mud type and condition, temperature or lithology – most likely to lead to bit-metamorphism. It would be reasonable to expect that better understanding would lead to improved practices and a reduction of the problem. Two benefits could be expected. First, unaltered cuttings would provide important geological information which is at present being lost. Second, FRIEDMAN ET AL. (1974) showed that the creation of glass in sliding friction experiments was accompanied by an increase in friction of about 25% above values at which no fusion occurred; this suggests that a reduction in drilling torque might be possible.

Finally, there are mutual advantages to be gained by an interchange of observations with metamorphic geologists, who are currently pursuing similar problems in deformed rocks.

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REFERENCES

Friedman, M., J. M. Logan & S. A. Rigert 1974 Glass-indurated quartz gouge in sliding-friction experiments on sandstone – Geol. Soc. Am. Bull. 85: 937-942.

Greer, R. T. 1971 The growth of colloidal silica particles. In: O. Johari (ed): Scanning electron microscopy – IIT Res. Inst., Chicago: 155-159.

Harker, A. 1939 Metamorphism. Methuen, London: 333 pp.

Jeans, C. V. 1978 Silicifications and associated clay assemblages in the Cretaceous marine sediments of Southern England – Clay Minerals 13: 101-126.

McKenzie, D. & J. N. Brune 1972 Melting on fault planes during large earthquakes – Roy. Astronom. Soc. Geophys. Jl. 29: 65-78.