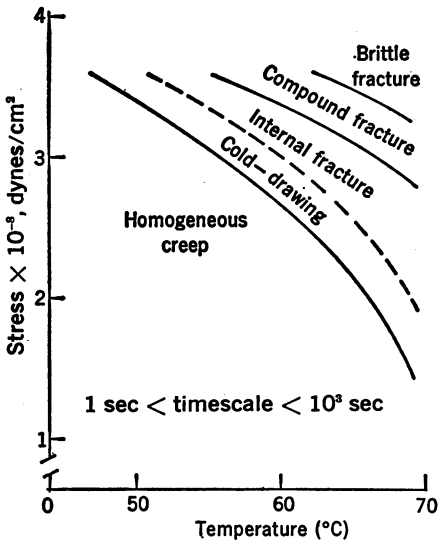

Fig. 2. Modes in which amorphous polyethylene terephthalate deforms. Definition of terms is given in the text. The broken line indicates that the boundary separating areas is not sharp and that two different modes of deformation can occur simultaneously, as in Fig. 1. The time interval during which these observations were made ranges from 1 to 1000 seconds following the application of load.

failure of the transparent strip (*4*) ("brittle fracture," Fig. 2). Specimens that deformed in more than one of the modes described above could also be prepared when stress and temperature were properly chosen (Fig. 1) (*4*, *5*).

The transformation of an optically clear polymer film to one that is highly opaque, indeed reflecting, is undoubtedly evidence of large-scale heterogeneity of the refractive index in the interior. We have observed that such heterogeneity disappears and the strip again becomes transparent whenever pressed firmly against a hard surface with a sharp edge (even with a fingernail). Furthermore, we find that the x-ray photograph of a lustrous film specimen does not show any crystalline reflections.

These findings are consistent with the conclusion that specimens of amorphous polyethylene terephthalate are capable of massive internal fracture, leading to void formation, while remaining macroscopically whole. Whether PET undergoes internal craze formation in the manner described for other polymers (*6*) is unknown, but the optical effect produced with PET is nevertheless remarkable, both in the suddenness with which it appears and in the brilliance achieved.

This phenomenon can be explained tentatively and qualitatively, if one recalls that amorphous polyethylene terephthalate is capable of crystallization under stress (*5*). The precise structural features of the crystallites so formed are still an unsettled issue. However, these centers of superior chain alignment are denser than the surrounding matrix and are, therefore, placed under tension by it. Should the lateral chain order induced by external stress give rise to a few, sufficiently large crystallites, the tension acting on them could be readily relieved by chain segment motion if the polymer were above its glass transition temperature, T_g. Such relief would not be forthcoming within the timescale of our experiments if the polymer were below T_g. The tension exerted on the crystallites by the matrix could then rise sufficiently to cause fracture of these crystallites and simultaneous nucleation of voids. The growth rate of such voids could be considered to be much faster than the rate of their nucleation, in which case these few voids would grow rapidly, coalesce, and cause the macroscopic failure of the specimen (brittle fracture). If, by contrast, the rate of void nucleation were much faster than the growth rate, voids would spread rapidly over the entire specimen, converting it into a highly extended and foamlike solid, but leaving it macroscopically intact (internal fracture). Should the void nucleation and growth rates be comparable in magnitude, intermediate cases might exist (compound fracture). Finally, both the void nucleation rate, as well as the growth rate, could be very slow compared to the duration of the experiment; in such a case, the polymer would simply form a neck and elongate extensively without forming voids, thereby preserving its transparence (cold-drawing).

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30 June 1969

Coesite from the Richat Dome, Mauritania: A Misidentification

Abstract. *The "shattered sandstone" from Richat reported to contain coesite is a tectonic breccia and probably represents a shear zone developed during the structural doming. An optical and x-ray examination of concentrates from this breccia demonstrated that the supposed x-ray reflections of coesite are actually due to barite, introduced into the permeable crushed zone by groundwater.*

Aside from the actual recovery of meteoritic material, the most definitive evidence of an impact origin for a large circular geomorphic structure is the presence of shock-induced metamorphic effects in the rocks and minerals of the structure. The most common features encountered in the field are impact glasses, shock breccias, and shatter cones. In the laboratory one looks for changes in the minerals themselves. The principal changes, any or all of which may be present, include intense random shattering of mineral grains; planar features (sets of closely spaced fractures lying along unusual crystallographic directions) in quartz, feldspars, pyroxenes, amphiboles, and carbonates; complete or partial vitrification of one or more minerals without melting (for example, maskelynite); kink-banding in micas; and the high-pressure polymorphs of silicon dioxide, coesite, and stishovite (*1*).

Richat—a dissected dome, 38 km in diameter, situated in the Mauritanian Adrar—has long been considered a possible astrobleme, mainly because of its circular symmetry and the occurrence of extensive breccia deposits near the center of the structure. In 1964, Cailleux *et al.* (*2*) reported the presence of coesite in a "shattered sandstone" (*grès secoué*) collected close to the center of the Richat structure. Their identification was made on the heavy fraction of a

powdered sample settled in bromoform (specific gravity, 2.85), which was analyzed by the Debye-Scherrer x-ray powder technique. Since, thus far, coesite has been found only in meteorite impact structures, this report gave strong support to the theory that Richat was the root structure of a large impact crater.

However, the coesite identification remained in doubt for two reasons. First, the x-ray data, as reported (Table 1), were not definitive. The two strong reflections corresponding to *d*-spacings of 3.42 Å and 3.07 Å are in agreement with those of coesite, but the intensity of the reflection at 4.38 Å is high by a factor of 4 and the intensity of the reflection at 2.71 Å is high by a factor of 3. Additional weak coesite reflections are not listed, presumably because Cailleux *et al.* felt they were masked by quartz reflections. Second, there is some doubt that shock-generated coesite could be concentrated by the method used. Shock-generated coesite occurs as small blebs and stringers, which are always embedded in glass of a much lower specific gravity (*3*). If the coesite is not freed from the enclosing glass, the specific gravity of the combination would be too low to permit separation in bromoform. But grinding the sample fine enough to free coesite from glass would probably result in a powder too fine to permit easy separation in a heavy liquid. Because of these presumed difficulties associated with separations in heavy liquids (to my knowledge there is no experimental verification of this), coesite is normally concentrated on the basis of its lower solubility in dilute hydrofluoric acid solutions, relative to quartz and glass.

In March 1968, I participated in an expedition to Richat, the primary purpose of which was to determine whether shock metamorphic effects were present in the rocks forming this structure. Our field work and laboratory examination of collected rocks failed to reveal a single feature which could be ascribed to explosive shock waves. Because the rock exposures are excellent and the rock types present should have preserved shock effects very well, we concluded that Richat was not the root structure of an ancient impact crater but was endogenous in origin (*4*).

The origin of the extensive chert breccias near the center of this structure remains enigmatic. But the quartzite and sandstone breccias, similar to the one described by Cailleux *et al.* as containing coesite, are clearly tectonic breccias and most likely represent shear zones developed in the doming event (*4*).

Table 1. Comparative x-ray diffraction data (most reflections of intensity less than 10 have been omitted) for heavy concentrates of shattered sandstone from Richat dome, synthetic coesite, and synthetic barite.

Heavy concentrate (*2*)		Synthetic coesite (*9*)		Heavy concentrate (this study)		Synthetic barite (*10*)	
d (Å)	*I*	*d* (Å)	*I*	*d* (Å)	*I*	*d* (Å)	*I*
				4.45		4.44	17
4.38	20	4.40	5	4.35		4.34	36
				3.90		3.90	57
				3.80		3.77	12
				3.60		3.576	31
3.42	70	3.432	50	3.45	80	3.442	100
				3.33	100*	3.317	67
3.07	70	3.098	100	3.10	80	3.101	97
		2.77	15	2.83		2.834	53
2.71	50	2.68	15	2.73		2.734	16
						2.726	47
				2.50		2.481	14
		2.303	10	2.32		2.322	15
		2.195	10	2.20		2.209	27
				2.10	90	2.120	80
						2.104	76
		2.034	10	2.05		2.056	23
		1.846	10	1.85		1.857	16
		1.789	10	1.80		1.787	3
		1.716	15	1.72		1.723	5

* This is also the strong quartz reflection

Therefore, if coesite were indeed present in these rocks, it would be the first documented occurrence of this mineral in a normal terrestrial environment, and it seemed advisable to attempt confirmation of the experiment of Cailleux *et al.*

A 100-g piece of the same rock Cailleux *et al.* had examined (*5*) was divided into two parts. Using his dilute hydrofluoric acid technique, which has proved so successful for rocks containing shock-generated coesite and stishovite, Fahey attempted to concentrate any coesite present in one part of the sample (*6*). Part of the remainder was ground to −120 mesh and allowed to separate in a solution of thallium malonate formate (Cargille) (specific gravity, 2.75 ± 0.01).

From a rock sample of approximately 50 g Fahey returned to me a concentrate weighing 520 mg. An x-ray powder photograph (*7*) of this concentrate included only quartz and zircon reflections. There was no suggestion of even the strongest coesite reflection.

The gravity separation yielded a heavy concentrate weighing 67 mg from an original sample of about 22 g. An x-ray powder photograph (*7*) of this concentrate contained a series of reflections remarkably close to those of coesite. Not only were all the reflections reported by Cailleux *et al.* present but also every other coesite reflection of intensity 10 or greater (on a scale of 0 to 100) could be accounted for.

However, additional reflections were also present, including the prominent reflection at 2.10 Å mentioned by Cailleux *et al.* as an unidentified reflection in their x-ray photograph. A microscopic examination revealed no coesite at all in this heavy concentrate, which consists entirely of barite plus some quartz. The barite is clean and well crystallized. Its optical characteristics, as determined in a series of fragment mounts, are both unequivocal and definitive. In thin section the barite is sparsely distributed in the crushed groundmass surrounding the breccia fragments (which are composed entirely of quartz grains).

The x-ray data (Table 1) demonstrate not only that there is a close match between the strong coesite reflections and barite reflections but also that barite accounts for all the "extra" reflections present in the Richat concentrate.

The conclusion is inescapable that Cailleux *et al.* mistook the barite reflections in their powder photograph for reflections generated by coesite plus quartz plus an unknown mineral. Instead of coesite produced by strong shear stresses in the tectonically shattered sandstones of Richat, there is only secondary barite introduced by groundwater into the more permeable, crushed zones of these rocks. An undisputed terrestrial occurrence of endogenous coesite remains to be discovered.

Barite is insoluble in hydrofluoric acid, and its absence from the acid

concentrate reported here results from the final step in Fahey's technique, which involves decanting a temporary suspensoid of fine-grained coesite after the coarser material has settled out (*6*). Thus, even with the acid-digestion method, a slightly different technique or a sample containing very fine-grained barite could result in a barite concentration. Since barite is a common secondary mineral in shear zones and breccia lenses, future workers should be aware of this problem. Barite is especially prevalent, for example, in the central United States, occurring in several well-known "cryptoexplosion" features (*8*). There are two possibilities: (i) barite may be mistaken for coesite; or (ii) the presence of barite (correctly identified) could make it difficult, if not impossible, to detect small amounts of coesite also present. The simplest way of avoiding these possibilities is to remove any barite present by treating the concentrate with hot sulfuric acid before attempting the coesite identification.

Note added in proof: C. Pomerol has subsequently supplied me with the complete x-ray data of Cailleux *et al.*; of the 28 reflections listed, virtually all are matched by barite or quartz reflections, or both.

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6 June 1969; revised 10 July 1969

Macquarie Island and the Cause of Oceanic Linear Magnetic Anomalies

Abstract. *Macquarie Island is formed of probably Pliocene oceanic crust. Intruded into pillow lavas is a belt of harzburgite and layered gabbro masses cut by dike swarms. Similar belt-like structures may cause the linear magnetic anomalies of the oceans.*

Macquarie Island lies in the Southern Ocean on the seismically active Macquarie Ridge (Fig. 1), about 1100 km south-southwest of the southern tip of New Zealand. The island is about 39 km long and 3 km wide and is elongated north-northeast parallel to the ridge axis.

Mawson (*1*) divided the rocks of the island into three groups: an older basic group of lavas, in places intensely folded, intruded by the ultramafic and mafic plutonic rocks of the gabbroid group, with both groups overlain unconformably by a younger basic group of pillow lavas and agglomerates. Furthermore, Mawson considered that the island had been glaciated by an ice sheet which moved east-southeast from a gathering ground to the west of the island where there is now deep sea (*2*). It was probably the idea of a folded "basement" and the suggestion of a foundered land mass to the west of this isolated oceanic island that led Holmes (*3*) to refer to Macquarie Island as a "geological enigma" and a "critical area" for the study of ocean tectonics. Our reinterpretation (*4*) of the geology of part of Macquarie Island shows that it is composed entirely of oceanic crust material and gives an account of dilational features compatible with modern theories of ocean tectonics and crustal genesis.

In the northern third of the island (Fig. 2) the oldest rocks are a group of pillow lavas with interstitial *Globigerina* ooze and hyaloclastite, block lava, breccia, and minor graywacke. Within this group, which corresponds to Mawson's younger basic group, there are rapid changes between the various rock types, both along and across the strike. At Bauer Bay and Langdon Bay there is overturned pillow lava (Fig. 2); at Mawson Point and Brothers Point angular discordances occur, and thin graded graywacke beds are intercalated with the volcanic rocks. Faulting is common.

Paleontological evidence (*5*) shows that the *Globigerina* ooze in the interstices between the pillows is probably Pliocene in age and was deposited in 2000 to 4000 m of cold water. Lithological and structural features suggest a sporadic buildup of material on the sea floor by the extrusion of thick submarine lava flows, the deposition of brecciated volcanic material, and the mixing of lava with fragmental volcanic material and abyssal plain sediment.

Intruded into the extrusive rocks are ultramafic and mafic bodies (Mawson's gabbroid group) and dike swarms (Mawson's older basic group). These intrusive rocks form a clearly defined belt, 4 km wide, trending 330° (true) obliquely to the long axis of the island. The age limits of this intrusive belt are set by the probable Pliocene age of the extrusive rocks and by the age of the glaciation which affected the island (*6*).

Intrusive activity took place in three stages. The earliest intrusions are of harzburgite which now occur as wedge-shaped bodies up to 150 m wide, elongated in a northwest direction. That a tensional stress field prevailed during serpentinization of the harzburgite is indicated by a set of near-vertical closely spaced anastomosing cracks filled with cross-fiber asbestos and oriented parallel to the mean regional trend of the lithological striping of the intrusive belt.

Later intrusions of gabbro also occur principally as wedge-shaped slices up to 1 km wide elongated in a northwest direction, although smaller bodies are common as dilational dikes in the ultramafic rocks and as wedge-shaped or planar screens within the dike swarms. Rhythmic layering is well developed in the gabbros in the central portion of the intrusive belt.

Dolerite dikes, 1 to 3 m thick, were intruded in the last stages of igneous activity. They occur in swarms, commonly dense enough to exclude the country rocks. Two main types of dolerite are present, a coarsely feldsparphyric type and an aphyric type. The phenocrysts of the feldsparphyric dikes are concentrated in their central portions and form swirls around irregularities in the dike walls, thus showing that the phenocrysts were present when the magma was being intruded (*7*).

The margins of the intrusive belt are