SHOCK-IMPLANTED NOBLE GASES IN SAMPLES FROM THE WABAR IMPACT CRATER:
IMPLICATIONS FOR OTHER TERRESTRIAL CRATERS AND THE SURFACE OF MARS.
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Experimental studies in the laboratory have shown that it is relatively easy to shock-implant noble gases and nitrogen into porous silicate materials (1,2,3). The quantity of shock-implanted noble gas is proportional to the pore volume and ambient gas pressure and increases with increasing shock stress up to about 20 GPa, above which the efficiency of gas implantation is close to 100% of all gas available. Noble gases implanted into a terrestrial basalt showed increasing activation energies to diffusion loss with increasing shock pressure, which for Ar ranged from approximately 7 kcal/mole at 2 GPa to 25-31 kcal/mole at 30-60 GPa (3). At these higher shock pressures the implanted gas is apparently retained within annealed lattice defects and is lost by diffusion no more readily than radiogenic Ar formed within the sample by decay of potassium. Shock-implantation of the Martian atmosphere is the likely explanation for the presence of gases within glass and other shocked phases of the Elephant Moraine 79001 meteorite (4), and the presence of these gases is a major argument for a Martian origin of EETA79001 and other shergottite meteorites.

Given the ease with which noble gases and N can be shock-implanted into silicates in the laboratory and the probable role of shock in implanting trapped gases into the EETA79001 shergottite, it seems natural to suppose that shock-implanted atmosphere should be found in shocked samples from terrestrial impact craters. A variety of materials from terrestrial craters have been analyzed, but we are not aware of any suggestion of shock-implanted atmospheric gas. Much of the literature data focuses on impact melts, which are not necessarily good hosts for implanted gases, as their high temperatures can cause the loss of volatiles, such as water loss in tektites (5). Many analyzed rocks are dense and non-porous, and experimental results suggest that these should not contain substantial quantities of implanted gases (1,3). Target rocks at many terrestrial craters resided below the water table, and their pore space was filled with water rather than ambient atmosphere. Furthermore, moderately shocked rocks characterized by solid state deformations typically contain weathering products which can adsorb significant quantities of atmospheric gases. Adsorbed gases are released at low temperatures in the laboratory, which is also the case for gases implanted at low (< 20 GPa) shock pressures. To identify shock-implanted gases in terrestrial samples requires that a significant quantity of implanted gas be present and that it reside in sites with relatively high activation energies.

We considered which terrestrial crater offered favorable conditions for shock-implantation of atmospheric gases (i.e., a dry, porous, chemically simple target material), and decided to analyze samples from the relatively young Wabar crater in Saudi Arabia. This crater, 90 meters in diameter, was formed by an iron meteorite impacting into a dry, porous target consisting largely of quartz sand (6). We measured the isotopic concentrations of the noble gases as a function of stepwise release temperature in two impact glasses, two shock-lithified clasts, and a sample of sand collected at this crater (and kindly supplied by K. Fredriksson of the Smithsonian Institution). Detailed petrographic and chemical analyses of these samples are given in (7). The clasts were several cm in diameter and contained approx. 18% (clast A) and 75% (clast B) impact melt, indicating shock levels of 25-30 GPa (clast A) and 40-45 GPa (clast B). The glasses analyzed were of the dark type and contained a few % meteoric contamination. The exact Wabar target is not known, and the loose surface sand may only approximate the target composition for these clasts (7).

The measured noble gases were essentially atmospheric in composition (including 40Ar/36Ar), except for a radiogenic 40Ar component in the sand, but varied among samples in concentration and in diffusive retentivity. Figure 1 compares pressure-normalized air-40Ar concentrations in these five Wabar samples with non-radiogenic Ar in several tektites and in three probable impact glasses of uncertain origin (Darwin glass, Libyan glass, Aouelloul Crater) (8), in glass and shocked clast samples from the Ries impact (1), in vesicular and non-vesicular glass samples from the Lonar impact structure (1), in glass from the EETA79001 shergottite (4), and in solid and powder samples of the terrestrial Servilleta basalt experimentally shocked to pressures of 30-60 GPa (1,3). The 40Ar concentration measured in EETA79001 was actually much lower, but has been normalized here for the factor of 200 difference in partial pressures of 40Ar between Earth and Mars. The Wabar glass and especially the clast samples have higher concentrations of atmospheric gases than other typical, terrestrial shocked materials. The two Wabar clasts samples showed gas concentrations larger than that seen in experimentally shocked solid samples of Servilleta basalt and nearly as large as that seen in shocked powdered samples of this basalt. Noble gases were implanted into powdered Servilleta with apparent efficiencies of 50-100% for experimental shock pressures above about 20 GPa. Figure 1 therefore suggests that the two Wabar clast samples contain atmospheric noble gases in concentrations approaching those expected for dry, moderately porous material such as sand or sandstone shocked to pressures of > 20 GPa. The surface sand shows the lowest gas content among the Wabar samples, and even much of the gas in the sand may be contained in a minor (3%) component consisting of impact melt and other shocked fragments.
In addition to containing large concentrations of atmospheric gases, much of the Ar, Kr, and Xe in these Wabar samples were released at relatively high extraction temperatures indicative of gases implanted by strong shock, but not of adsorbed gases. In experimental studies on a basalt we found that the activation energies and release temperatures for diffusion loss of shock-implanted noble gases tend to increase with increasing shock pressure (3). For example, the activation energy, Q, for diffusive loss of Ar from basalt samples shocked to 2, 5, 20, 35, and 59 GPa was 7, 9, 14, 25, and 31 kcal/mole, respectively. Although not all of the Wabar samples show linear Arrhenius plots for Ar diffusion, we have estimated the values of Q for Ar diffusion for that gas which releases above 500°C, a temperature which is expected to have degassed most adsorbed gases. The values of activation energy, Q, so estimated are 32-33 kcal/mole for the clast-B, glass-B, and sand samples, and 46 kcal/mole for Wabar clast-A. These are relatively high activation energies and are consistent with volume-correlated Ar in shocked silicate.

The relatively large concentrations of atmospheric noble gases released with high activation energies from the Wabar clasts strongly suggest that these gases were shock-implanted by the Wabar impact. Significant concentrations of shock-implanted gases are not commonly found in shocked samples from other terrestrial craters, probably because of factors mentioned above. The Wabar crater site is, however, favorable for the observance of shock-implanted gases, and we note its similarity to conditions on the surface of Mars. The Martian surface may contain numerous shock-lithified samples as a result of past cratering, and many of these samples may contain unfractured, shock-implanted gas from the Martian atmosphere. If the composition of the Martian atmosphere has varied over the history of the planet, then a record of this variation may be preserved in shocked crater ejecta.