ELECTRON DAMAGE: A NEW ANALYTIC TECHNIQUE APPLIED TO PLAGIOCLASE IN SHOCKED CHONDRITES AND BASALT, Raymond Jeanloz, Seismological Laboratory, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125.

Prior studies (1,2) have shown that artificially and naturally shock-produced plagioclase glasses exhibit sodium loss under the electron beam during microprobe analysis. This effect has also been described in fused plagioclase and Na(Ca)-bearing silicate glasses (3-9). The mechanism for this sodium instability has been discussed in (1,9) and references therein. Originally stable plagioclase was shown to become destabilized (lose sodium under the electron beam) as a result of shock (1), and it has been suggested (1,2) that degree of sodium instability appears to correlate with intensity of shock deformation (presumably related to peak shock pressure).

In order to better understand and quantify this effect, numerous microprobe analyses of sodium concentration vs. time were performed on fused (synthetic) plagioclase glasses over a range of compositions (An00-An100) and under different operating conditions. Initially, sodium concentration (i.e., counts per second on the Na Kα peak) decreases linearly with time, however, at some characteristic time (t1) counts per second (cps) drop off exponentially with time. This produces a kink or knee at t1 on a plot of cps vs. time. Previous observations (e.g., 9) are compatible with this two-stage process. Values of the slope or exponents in the time-dependency of cps do not correlate well with changes in microprobe operating conditions, however, t1 (sec) is well described by the following relation:

\[
\ln(t_1) = \alpha \ln(SC) + \beta(D) + \gamma(X) + F
\]

where SC is current density (measured as sample current on brass in nA), D is beam (spot) diameter (μm), X gives Na content (mol% anorthite component), and \( \alpha = -0.9, \beta = 0.1, \gamma = 5.2 \) and \( F = 3.5 \) are constants determined for the fused plagioclase glasses. In this study, accelerating voltage was constant at 15 kV. Eqn. 1 is useful in predicting the operating conditions required for the reliable (stable) microprobe analysis of a plagioclase glass of given composition.

Using Eqn. 1, one can compare measured values of t1 (the onset of exponential decay of cps) for any sample (unknown) with the predicted value (t10) for the fused glass of identical composition (considered as a standard) for given operating conditions. An index of stability (C*) can then be defined by:

\[
C^* = \frac{\ln(t_1) - \ln(t_1^0)}{\ln(t_1) + \ln(t_1^0)}
\]

Note that \( C^* \to \infty \) for infinitely stable analyses, whereas \( C^* = 0 \) implies identical electron damage behavior for the sample and the fused glass standard.

Experimentally shocked basalt samples and (naturally) shocked chondrites have been analyzed (Table 1; plagioclase compositions of An45-An55 and...
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An$_{10}$–An$_{13}$ respectively (1,2)). Figure 1 summarizes C$^*$ values for analyses on the samples obtained to date. Unshocked plagioclase from the Vacaville basalt (01) and lightly shocked, non-diaplectic plagioclase (333) show large (i.e., stable) values of C$^*$. However, the highly shocked basalts have low C$^*$, with C$^*$ correlating well with increase in shock intensity and observed shock effects (samples 303, 300, 302 in order). Likewise, meteorite samples studied show a good correlation between decreasing C$^*$ and increasing shock deformation (based on petrography (2,11)) with lightly shocked Oakley giving stable analyses, and successively more deformed Cedar, Bruderheim, Fisher and Coon Butte giving decreasing C$^*$. These preliminary data indicate that Fisher and Coon Butte have suffered shock of intensity analogous to (or slightly less than) samples 303 and 300 respectively – all consistent with petrographic observation. C$^*$ appears to be a more reliable index of deformation than the Na index of (2) shown in Table 1.

Though the data are sparse for some samples (e.g., Bruderheim) and potentially large error bars are associated with the stable analyses, C$^*$ is clearly a good stability index reflecting degree of disorder and thus intensity of shock deformation of shocked plagioclase. Thus, electron damage analysis can be used to map deformation on a scale of microns and to pick out differences in shock deformation between different shock-produced plagioclase glasses, otherwise (petrographically) a difficult task at best. Spatial resolution, ease of analysis and the essentially non-destructive nature of this approach offers some immediate advantages over the complementary IR and X-ray techniques.

Three further, intriguing points emerge. It appears that fusion (by shock) occurs at about the point that C$^*$ approaches 0 (sample 300). From the definition of C$^*$ this is not surprising, perhaps, but might lead to the speculation that Coon Butte (for example) was shocked almost to the point of incipient melting. Furthermore, more intense shock leads to unquestionable negative values of C$^*$ both for individual points and for a sample average (sample 302). As in (1), this suggests the possibility that shock can produce anomalously highly disordered glasses. This hypothesis is not incompatible with the results of IR studies of shocked minerals (12,13).

Significantly, C$^*$ values demonstrate a measurable spread, not only within a sample, but even within an individual grain. For example, Coon Butte run 01-08 is from a grain with C$^*$ values clustering around 1.0. In another grain, run 01-05 was measured less than 50 µm from a C$^*$ value of -5.0. The range of C$^*$ values observed within samples and, particularly, within single grains provides strong evidence for wide variations in shock deformation on a scale of microns. This variation is analogous to well documented variations found on both smaller and larger scales (electron microscopy to hand sample and outcrop observations) and undoubtedly reflects the detailed complexities of shock metamorphism in rocks.

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(4) Ribbe and Smith (1966) J. Geol., 74, 217.

Table 1

<table>
<thead>
<tr>
<th>Sample</th>
<th>Shock Effects</th>
<th>C*&lt;sup&gt;a&lt;/sup&gt;</th>
<th>O&lt;sub&gt;2&lt;/sub&gt;&lt;sup&gt;b&lt;/sup&gt;</th>
<th>O&lt;sub&gt;2&lt;/sub&gt;&lt;sup&gt;c&lt;/sup&gt;</th>
<th>C*&lt;sup&gt;d&lt;/sup&gt;</th>
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<tbody>
<tr>
<td>Coon Butte</td>
<td>F</td>
<td>0.80</td>
<td>H</td>
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<tr>
<td>Fisher</td>
<td>F</td>
<td>0.35</td>
<td>H</td>
<td>6</td>
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<tr>
<td>Bruderheim</td>
<td>D</td>
<td>0.78</td>
<td>H-M</td>
<td>28</td>
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</tr>
<tr>
<td>Cedar</td>
<td>B</td>
<td>1.00</td>
<td>H-J</td>
<td>72</td>
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</tr>
<tr>
<td>Oakley</td>
<td>A</td>
<td>1.03</td>
<td>Large</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vassamille Basalt</td>
<td>(experimentally shocked)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>301</td>
<td>Substantial fusion</td>
<td>-2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>Grain boundary melting</td>
<td>1</td>
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<td></td>
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<tr>
<td>304</td>
<td>Deplastic</td>
<td>5</td>
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<tr>
<td>333</td>
<td>Crystalline</td>
<td>Large</td>
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<tr>
<td>34</td>
<td>Unchanged</td>
<td>Large</td>
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</table>

(a) Petrographic description: A (light) to F (heavy) shock effects from (2)
(b) Na (observed) /Na (calculated): based on microprobe analyses, quoted from (2)
(c) Petrographic description: H (heavy), M (medium) deformation from (11)
(d) Approximate mean value, see Figure 1

Figure 1. Values of the stability index C* for shocked chondrites and experimentally shocked samples shown as histograms. Single analyses are given with error bars while limiting values from analyses are shown as half error bars with arrows.