REVIEW ARTICLE

OBSIDIAN IN THE MEDITERRANEAN AND THE NEAR EAST:
A PROVENANCING SUCCESS STORY*

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Obsidian provenancing studies comprise one of the most productive and successful research programmes of archaeological science. Obsidian characterization has been successful because workable obsidian is homogeneous on a small scale, analysable by a large number of methods, and is restricted to a small number of mainly readily distinguishable geological sources. Analytical, dating, source, and trade studies within the western Mediterranean, central and eastern Europe, the Aegean, and Anatolia and the Near East during the last 30 years or so are reviewed. Research has shown that distributions are mainly separate in the four regions examined, and that obsidian was traded up to 900 km in the prehistoric period. Publications on obsidian in the areas under review reached a peak of frequency in the later 1970s and 1980s, but have now decreased in number. This may reflect changing fashions in archaeometric studies, and a current lack of routine application of the provenancing methods developed.

KEYWORDS: MEDITERRANEAN, NEAR EAST, ANATOLIA, CENTRAL EUROPE, EASTERN EUROPE, SARDINIA, LIPARI, PANTELLERIA, PONTINE ISLANDS, MELOS, GIALI, CARPATHIANS, ACIGÖL, ÇIFTLIK, BINGÖL, LAKE VAN, ARMENIA, PALAEOLITHIC, NEOLITHIC, BRONZE AGE, INSTRUMENTAL NEUTRON ACTIVATION ANALYSIS, X-RAY FLUORESCENCE, MICROPROBE, BETACOUNTING, OPTICAL EMISSION SPECTROSCOPY, ATOMIC ABSORPTION SPECTROSCOPY, FISSION TRACK, K/AR, HYDRATION LAYER, MÖSSBAUER SPECTROSCOPY, MAGNETISM, PROTON INDUCED GAMMA EMISSION, INDUCTIVELY-COUPLED PLASMA EMISSION SPECTROSCOPY, ISOTOPES, OBSIDIAN, CHARACTERIZATION, PROVENANCE, TRADE

INTRODUCTION

Obsidian characterization is one of the success stories of archaeological science. The shiny volcanic glass is a frequent find in many Stone Age contexts of the world. It is imperishable, attractive and easily recognizable, a desirable commodity to prehistoric people in need of artefact raw materials. Add to this the facts that obsidian is generally chemically homogeneous, analysable by a host of methods, and can only come from a restricted number of sources, and it becomes almost an ideal subject for archaeological provenancing. Research aimed at tracing the origins of archaeological obsidian back to its source outcrops has spawned hundreds of scientific papers, utilizing a score or more of characterizing techniques. It is now over 30 years since Cann and Renfrew (1964) led the way in showing how chemical characterization of obsidian can demonstrate cultural contact, thus opening up a new discipline of interpreting these contacts in terms of trade. The history of obsidian

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characterization, therefore, offers an opportunity to assess the approaches and achievements of archaeological science in this area.

In this paper, obsidian and its close petrological relatives will be defined, and obsidian studies, mainly within Europe, the Mediterranean area, Anatolia and the Near East, will be reviewed. It is not the intention to describe work in the Americas or circum-Pacific countries, except where a technique or development is especially significant. Obsidian studies, for the purposes of this review, will include analytical characterization studies, dating work where undertaken with archaeological objectives, obsidian source (outcrop) surveys, statistical studies of obsidian data, and discussions of obsidian trade/transport and exchange mechanisms. Purely geological studies of obsidian are included when describing source/outcrop areas and obsidian classifications.

Variations in approaches to obsidian characterization during the last 30 years will be considered, and with the benefit of hindsight it may be possible to assess which were the most appropriate methods. Obsidian was one of the first, most intensively studied, and most successful provenancing programmes of archaeological science. Perhaps it is now possible to understand why it was so popular, and where all the work has led.

DEFINITIONS AND DESCRIPTIONS OF OBSIDIAN AND CLOSELY-RELATED ROCKS

Obsidian is a volcanic rock of intermediate to acid chemical composition, composed entirely or almost entirely of glass. It is formed when a lava of high silicon and aluminium content is chilled rapidly at the earth's surface, so that the nucleation and growth of crystals is inhibited. Obsidian-forming lavas are typically rhyolitic in composition with SiO₂ concentration greater than c. 66%, but glasses can also be formed by rapid chilling of lower-silica melts such as those of dacite or trachyte composition, or even, in exceptional circumstances, of basic lavas which, when cooled more slowly, would form a basalt. Some obsidians do contain a proportion of crystals—up to about 15%—and these will be minerals appropriate to the chemical type of obsidian. For example, rhyolitic obsidian may contain crystals normally associated with rhyolites, including quartz and alkali feldspars. Obsidian may also contain some gas bubbles (vesicles) resulting from gases exsolving out of the material. However, the presence of large amounts of volatiles (water, gases) within a lava will prevent the formation of a homogeneous obsidian, resulting instead in a fragmented volcanic tuff or bubbly pumice. Obsidian typically has a refractive index of about 1.50 and a density of between 2.35 and 2.40 g/cm³ (figures taken from Cann 1983).

Since glasses are unstable in nature, obsidian gradually devitrifies as diffusion processes promote nucleation and growth of crystal forms, sometimes aided by re-heating or by percolation of fluids within the material. Devitrification may result in the formation of spherulites within obsidian, spherical structures consisting of radially-disposed needle-shaped crystals. Obsidian also gradually hydrates over time, at a rate determined largely by composition and ambient temperature, taking up water to form a hydration layer whose thickness on artefacts may be measured to give a date of exposure of a worked surface (e.g., Friedman and Smith 1960; Friedman et al. 1966 and 1971; Sayre et al. 1988, including a survey of recent developments in the technique, by Ericson (1988); also reviews in Cann 1983 and Taylor 1976). Water uptake of up to 5% by weight can lead to perlitic texture, that is, concentric ‘onion-skin’ cracking patterns. Much of the obsidian hydration layer
work carried out has been done in the U.S.A., and very little has been applied to artefact
dating in Europe and the Near East.

The petrography, petrogenesis and geochemistry of obsidian are described in many
textbooks (e.g., Hatch et al. 1961; Cox et al. 1979), and recent discussions of the behaviour
of trace elements in rocks, and the use of element and isotope variation diagrams, are in
(1992) discuss the chemistry of, respectively, peralkaline and subalkalic obsidians. Cann’s
(1983) summary also provides insight useful to much archaeological obsidian work.

Obsidians are often classified chemically according to their contents of the oxides of
aluminium, calcium and the alkalis sodium and potassium (Fig. 1). Thus, peralkaline
obsidians are those with greater molecular Na₂O plus K₂O than Al₂O₃, while the subalka-
line obsidians have less molecular Na₂O plus K₂O than Al₂O₃. Peraluminous obsidians have
greater molecular Al₂O₃ than CaO plus Na₂O and K₂O, while metaluminous obsidians have
less aluminium than CaO plus Na₂O and K₂O. Within these divisions, calc-alkaline and
alkaline obsidians have, respectively, high CaO and alkalis, and high alkalis (but low
calcium) relative to SiO₂. Calcic obsidians are those with high CaO and, typically, low
alkalis relative to SiO₂. Macdonald et al. (1992) discuss the several classifications which have
led to these groupings, and point out that the terms calc-alkalic and alkali obsidians are
often used with undefined or contrasting definitions. However, since these terms are
established and useful descriptive words, Macdonald et al. (1992, 13 and fig. 4) recommend
their continued usage, as defined on a diagram of SiO₂/Na₂O + K₂O vs. CaO contents.

Typical chemical compositions of obsidian with SiO₂ contents of between 63–76% are
given in Cann (1983), who includes examples of calc-alkaline, peralkaline and alkaline
obsidians. Representative analyses of obsidians from important sources discussed in this
article are given in Table 1.

Variation in the concentrations of major elements (weight %) and trace elements (ppm or
µg/g) between and within suites of obsidians are the result of geological processes. These
reflect differences in the composition of the rocks which are melted to produce the magmas,
the physical conditions of melting, and modifications in composition due to processes

Figure 1  Diagram showing the chemical classification of obsidians (adapted from Macdonald et al. 1992, fig. 6).
Table 1  Chemical analyses of obsidians

<table>
<thead>
<tr>
<th>Locality</th>
<th>Lipari Papese</th>
<th>Sardinia Monte Arci-Uras</th>
<th>Pontine Isles Palmarola</th>
<th>Pantelleria</th>
<th>Central Europe Szöllöské</th>
<th>Aegean-Melos Ag. Nychia</th>
<th>Aegean-Giali</th>
<th>Central Turkey Karapinar-Agiböl</th>
<th>Lake Van Nemrut Dag</th>
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</thead>
<tbody>
<tr>
<td>SiO2 (%)</td>
<td>74.1</td>
<td>74.3</td>
<td>73.87</td>
<td>71.65</td>
<td>76.81</td>
<td>75.94</td>
<td>76.83</td>
<td>73.48 ± 1.14</td>
<td>72.51</td>
</tr>
<tr>
<td>TiO2</td>
<td>0.07</td>
<td>0.09</td>
<td>0.09</td>
<td>0.23</td>
<td>0.07</td>
<td>0.15</td>
<td>0.07</td>
<td>0.09 ± 0.05</td>
<td>0.29</td>
</tr>
<tr>
<td>Al2O3</td>
<td>13.23</td>
<td>13.83</td>
<td>13.47</td>
<td>7.6</td>
<td>12.99</td>
<td>13.11</td>
<td>13.34</td>
<td>13.11 ± 0.7</td>
<td>11.75</td>
</tr>
<tr>
<td>Fe2O3</td>
<td>1.83</td>
<td>1.55</td>
<td>1.83</td>
<td>8.66</td>
<td>1.1</td>
<td>1.31</td>
<td>1.23</td>
<td>1.2 ± 0.33</td>
<td>1.92</td>
</tr>
<tr>
<td>FeO</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.41</td>
</tr>
<tr>
<td>MnO</td>
<td>0.08</td>
<td>0.07</td>
<td>0.07</td>
<td>0.28</td>
<td>0.05</td>
<td>0.08</td>
<td>0.08</td>
<td>0.04</td>
<td>0.13</td>
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<tr>
<td>MgO</td>
<td>0.11</td>
<td>0.17</td>
<td>0.11</td>
<td>0.09</td>
<td>0.13</td>
<td>0.25</td>
<td>0.16</td>
<td></td>
<td>0.01</td>
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<tr>
<td>CaO</td>
<td>0.71</td>
<td>0.58</td>
<td>0.47</td>
<td>0.94</td>
<td>0.94</td>
<td>1.26</td>
<td>0.62</td>
<td>0.96 ± 0.36</td>
<td>0.32</td>
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<tr>
<td>Na2O</td>
<td>4.24</td>
<td>3.7</td>
<td>4.66</td>
<td>6.86</td>
<td>3.49</td>
<td>4</td>
<td>3.85</td>
<td>4.67 ± 0.51</td>
<td>5.55</td>
</tr>
<tr>
<td>K2O</td>
<td>4.86</td>
<td>4.97</td>
<td>4.65</td>
<td>4.29</td>
<td>4.37</td>
<td>3.24</td>
<td>4.06</td>
<td>4.43 ± 0.43</td>
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<td>P2O5</td>
<td>0.03</td>
<td>0.07</td>
<td>0.04</td>
<td>0.03</td>
<td>0.03</td>
<td>0.04</td>
<td>0.04</td>
<td></td>
<td>0.01</td>
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<tr>
<td>H2O + LOI</td>
<td>0.76</td>
<td>0.67</td>
<td>0.71</td>
<td>0.67</td>
<td>0.61</td>
<td>0.74</td>
<td>0.74</td>
<td>1.36 ± 0.10</td>
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<td>Nb (ppm)</td>
<td>64.1</td>
<td>441</td>
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<td></td>
<td>8.9</td>
<td>20</td>
<td></td>
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<tr>
<td>Zr</td>
<td>208</td>
<td>93</td>
<td>325</td>
<td>1976</td>
<td>124</td>
<td>114</td>
<td></td>
<td></td>
<td>790</td>
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<tr>
<td>Y</td>
<td>38.3</td>
<td>29.3</td>
<td>43.3</td>
<td>183</td>
<td>15.3</td>
<td>13.8</td>
<td></td>
<td></td>
<td>46</td>
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<tr>
<td>Sr</td>
<td>19.7</td>
<td>36.4</td>
<td>0</td>
<td>5.7</td>
<td>117</td>
<td>84.6</td>
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<tr>
<td>Rb</td>
<td>329</td>
<td>269</td>
<td>496</td>
<td>195</td>
<td>163</td>
<td>121</td>
<td>149</td>
<td>125 – 248</td>
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<tr>
<td>Zn</td>
<td>59</td>
<td>68.8</td>
<td>56.3</td>
<td>244</td>
<td>46.9</td>
<td>44.4</td>
<td></td>
<td></td>
<td>143</td>
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<tr>
<td>Co</td>
<td>2.9</td>
<td>3.1</td>
<td>3</td>
<td>0.46</td>
<td>3.4</td>
<td>3.5</td>
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<td>3.5</td>
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<tr>
<td>Cr</td>
<td>0.3</td>
<td>0.5</td>
<td>0.4</td>
<td>0.5</td>
<td>0.8</td>
<td>0.2</td>
<td></td>
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<td>0.2</td>
</tr>
<tr>
<td>V</td>
<td>15.1</td>
<td>18.2</td>
<td>18.9</td>
<td>32.7</td>
<td>26.3</td>
<td>21.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ba</td>
<td>314</td>
<td>299</td>
<td>336</td>
<td>614</td>
<td>543</td>
<td>554</td>
<td>777</td>
<td></td>
<td>10 – 108</td>
</tr>
</tbody>
</table>

No entry means not determined, 0 means not detected. When there is no entry for FeO, iron is total iron as Fe2O3 %. Data sources: Lipari, Sardinia, Pontine Isles, Pantelleria, Aegean: Francaviglia (1984, tables 1 – 3, 5); central Europe: Thorpe (1978); central Turkey: Innocenti et al. (1982a, table 4, average of five rhyolites from Karapinar-Agiböl); Lake Van: major elements Innocenti et al. (1982a, table 7, DY1 from lava dome 2 km east of Nemrut volcano), and (trace elements) Schneider (1990, table 1, 'Nemrut Dag'). Note that the sample from Nemrut Dag volcano is not strictly peralkaline (Al2O3 is slightly higher than Na2O + K2O), but is very near that compositional field and has the characteristic trace element signature of peralkaline obsidians.
which occur in the magma chamber, such as the crystallization and removal of minerals from the cooling magmas prior to their eruption as lavas (e.g., Wilson 1989; Cox et al. 1979).

Trace element abundances can vary by orders of magnitude between sources, while major elements are constrained within much narrower limits. Traces, therefore, offer a better chance of unambiguous source characterization, and are frequently used in archaeological work. Gross variations are particularly apparent between obsidians of different chemical (major element determined) type and tectonic setting. Thus, for example, Cann (1983) describes the differing behaviour of Zr and Nb, much more soluble in peralkaline melts than calc-alkaline, leading to a ready distinction between, say, the peralkaline obsidian of Pantelleria and alkaline/calc-alkaline sources on Lipari and Melos. Similarly, the variation, by orders of magnitude, in Zr and Ba formed the basis of early Mediterranean source distinctions (Cann and Renfrew 1964).

Obsidian is generally associated with young (less than 10 Ma) volcanic rocks, since older glasses will often have become devitrified to form felsites. Volcanic island arcs (destructive plate margins) produce typically calc-alkaline and more rarely alkaline obsidians, for example, in Melos and Lipari. Peralkaline obsidians are more commonly produced at within-plate volcanic settings (e.g., the obsidians of Pantelleria) and continental rifts. The sources relevant to studies reviewed in this paper include alkaline, calc-alkaline and peralkaline obsidians, and are listed in Table 2, with their tectonic settings and chemical type, and references to geological as well as archaeometric literature.

Outcrop form (noted in Table 2) varies from massive flows, such as the occurrences on Lipari Island, to small nodules of glassy obsidian only a few centimetres across remaining within a perlitized matrix, noted by Williams-Thorpe and Nandris (1977) in Hungary. Sources in this latter region also produce rounded pieces with pitted, weathered surfaces. Obsidian is generally black or grey in colour, although peralkaline obsidian tends to be green or brown due to its higher iron content. Sardinian obsidian is occasionally red, as are small pieces from central France (author’s observations for both these areas), but other exotic coloured glasses seen by the author—blue, and yellow—have turned out to be slags or other artificial glasses. Francaviglia (1984, 314) dismissed red Sardinian obsidian as a confusion with jasper, but noted a piece of blue obsidian found on that island by Professor Puxeddu.

Devitrification crystallites can appear as opaque bands, and spherulites as white spots. Appearance can be helpful in determining source: Melian obsidian is said to be ‘pearly’, Giali material is white spotted (Renfew et al. 1965), and the Carpathian sources divide into translucent and non-translucent types (Williams-Thorpe et al. 1987). The distinction between grey calc-alkaline and green peralkaline obsidian can be an excellent first step in sourcing in areas where both types are used (e.g., Cann and Renfrew 1964 on Malta). The green peralkaline obsidian of Pantelleria is distinctive enough to aid in provenancing Roman pottery, which is girtted with Pantellerian volcanic rock (Peacock 1982).

Obsidian was a desirable commodity to Stone Age cultures because of its properties of flaking with a predictable conchoidal fracture, and of retaining a sharp cutting edge. For these reasons it was used extensively within the Palaeolithic to Bronze Age and Chalcolithic periods in Europe and the Near East for the manufacture of, very frequently, blade tools, and of flaked artefacts, for example, arrowheads. A more specialized use was for decorative articles such as bowls (see, e.g., illustrations in Dixon et al. 1968). Crystallized, vesicular or
<table>
<thead>
<tr>
<th>Locality</th>
<th>Source names</th>
<th>Geological setting</th>
<th>Geological age</th>
<th>Obsidian type</th>
<th>Characteristics, colour</th>
<th>Important references</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIPARI</td>
<td>Gabellotto</td>
<td>Volcanic island arc</td>
<td>11.4 ± 1.8 Ka</td>
<td>Alkaline/calc-alkaline</td>
<td>Typically grey translucent, sometimes brown. Large flows and pieces in pumice</td>
<td>Keller 1982; Hallam et al. 1976; Thorpe 1978; Bigazzi and Bonadonna 1973; Pichler 1967 and 1968; Francaviglia 1984</td>
</tr>
<tr>
<td></td>
<td>Aquacalda</td>
<td></td>
<td>21 ± 4 Ka</td>
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<td></td>
<td>Monte S. Angelo</td>
<td></td>
<td>39.4 ± 2 Ka</td>
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<td></td>
<td>Rocche Rosse</td>
<td></td>
<td>1.4 ± 0.45 Ka</td>
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<tr>
<td></td>
<td>Forgia Vecchia</td>
<td></td>
<td>1.6 ± 0.38 Ka</td>
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<tr>
<td></td>
<td>Papasca beach</td>
<td></td>
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<td>SARDINIA</td>
<td>Monte Arci</td>
<td>Within-plate rifting</td>
<td>5.92 ± 0.53 to 2.8 ± 0.2 Ma</td>
<td>Calc-alkaline and mildly alkalic</td>
<td>Grey, slightly translucent, occasionally red. No large flows but pieces up to tens of cm</td>
<td>Beccaluva et al. 1976–7; Assorgia et al. 1976; Puxeddu 1958; Tykot 1992; Bigazzi et al. 1971; Belluomini 1970</td>
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<tr>
<td></td>
<td>S. Pietro and S. Antioco</td>
<td>Subduction zone</td>
<td></td>
<td></td>
<td>Pitchy, not very translucent. Rare use only reported</td>
<td>Dostal et al. 1982; Araña et al. 1974; Francaviglia 1984</td>
</tr>
<tr>
<td>PONTINE IS</td>
<td>Monte della Tramontana</td>
<td>Crustal extension</td>
<td>1.7 ± 0.3 Ma</td>
<td>Alkaline</td>
<td>Grey, more crystals than Lipari; small pieces only</td>
<td>Buchner 1949; Barberi et al. 1967; Bigazzi et al. 1971; Francaviglia 1984</td>
</tr>
<tr>
<td>(PALMAROLA)</td>
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<tr>
<td>PANTELLERIA</td>
<td>Balata dei Turchi, Lago di Venere, Gelkhamar?</td>
<td>Within-plate</td>
<td>Balata dei Turchi: 0.135 ± 0.016 Ma</td>
<td>Peralkaline</td>
<td>Dark green, occurs as lumps in pumice and tuffs</td>
<td>Civetta et al. 1988; Mahood and Hildreth 1986; Francaviglia 1988; Bigazzi et al. 1971</td>
</tr>
<tr>
<td>HUNGARY</td>
<td>Tokaj, Erdőbénye, Csepegő Forras, Tolesva</td>
<td>Volcanic arc</td>
<td>Miocene–Pliocene 3.86 ± 0.24 Ma 3.37 ± 0.27 Ma</td>
<td>Calc-alkaline</td>
<td>Grey, black, not very translucent. Small pieces not flows</td>
<td>Williams and Nandris 1977; Williams-Thorpe et al. 1984b; Biró 1981 and 1984; Durrani et al. 1971</td>
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<tr>
<td>Locality</td>
<td>Source names</td>
<td>Geological setting</td>
<td>Geological age</td>
<td>Obsidian type</td>
<td>Characteristics, colour</td>
<td>Important references</td>
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<tr>
<td>MELOS</td>
<td>Dhemenegaki</td>
<td>Volcanic island arc</td>
<td></td>
<td>Calc-alkaline</td>
<td>'Pearly' lustre, grey, non-translucent</td>
<td>Keller 1982; Fytikas et al. 1986; Durrani et al. 1971; Torrence 1979a, 1982, and 1986; Renfrew et al. 1965</td>
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<tr>
<td></td>
<td>Adhamas/Sta or Ag. Nychia</td>
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<td>GIALI</td>
<td>Volcanic island arc</td>
<td></td>
<td>2.01 ± 0.26 Ma</td>
<td>Calc-alkaline</td>
<td>White spots (spherulites)</td>
<td>Keller 1982; Durrani et al. 1971; Wagner et al. 1976; Torrence and Cherry 1976</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8.04 ± 0.65 Ma</td>
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<td></td>
<td></td>
<td>0.024 Ma</td>
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<tr>
<td>CENTRAL TURKEY</td>
<td>Acigöl, Göldag, Karaçaoğlan, Helvadere, Kayırlı, Çiftlik, Kömürçü, Bözköy</td>
<td>Continental collision zone</td>
<td></td>
<td>Calc-alkaline</td>
<td>Black, grey, some brown, translucent</td>
<td>Gratuzu et al. 1993; Innocenti et al. 1982a; Renfrew et al. 1966; Durrani et al. 1971</td>
</tr>
<tr>
<td>(CAPPADOcia)</td>
<td></td>
<td></td>
<td>Acigöl:</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>1.95 ± 0.33 Ma</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>8.14 ± 0.59 Ma</td>
<td></td>
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<tr>
<td>TAURUS</td>
<td>Bingöl, Cavuslar, Orta Duz, Alatepe, Catalak</td>
<td>Subduction zone and post-subduction alkaline volcanism</td>
<td>Upper–Middle Miocene and Quaternary</td>
<td>Peralkaline (area also has calc-alk. and alk. rocks)</td>
<td>Includes some green or brown</td>
<td>Gratuzu et al. 1993; Innocenti et al. 1982a and 1982b; Renfrew et al. 1968</td>
</tr>
<tr>
<td>Locality</td>
<td>Source names</td>
<td>Geological setting</td>
<td>Geological age</td>
<td>Obsidian type</td>
<td>Characteristics, colour</td>
<td>Important references</td>
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<tr>
<td>LAKE VAN</td>
<td>Nemrut Dag</td>
<td>Subduction-related</td>
<td>Quaternary</td>
<td>Mildly peralkaline</td>
<td>Mainly green, some</td>
<td>Gratuz et al. 1993; Innocenti et al. 1980,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>volcanic arc</td>
<td></td>
<td>peralkaline</td>
<td>black</td>
<td>1982a and 1982b; Renfrew et al. 1966</td>
</tr>
<tr>
<td>ARMENIA/</td>
<td>Seven, Kars, Erevan,</td>
<td>Subduction-related</td>
<td>Pliocene</td>
<td>Calc-alkaline; also alkaline</td>
<td>Some grey</td>
<td>Gratuz et al. 1993; Renfrew et al. 1966;</td>
</tr>
<tr>
<td>VAN REGION</td>
<td>Sarikamis, Bayezid</td>
<td>volcanic arc</td>
<td>Quaternary</td>
<td>rocks in this area</td>
<td></td>
<td>Innocenti et al. 1982a and 1982b; Renfrew</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>and Dixon 1976</td>
</tr>
</tbody>
</table>
very devitrified obsidian is not suitable for tool manufacture because it loses its predictable fracture on flaking. Renfrew et al. (1965) summarize later, Classical, use of obsidian for mirrors, seals, statues and tesserae, and note its mention by Pliny (Natural History, xxxvi. 196). As far as the present author is aware, no provenancing work has been done on these later finds, and this review will concentrate on obsidian in prehistoric contexts.

Obsidian can be dated geologically (i.e., to the time of cooling of the lava) by several methods, giving information which may be used for characterization and provenancing of artefacts. Fission track and K/Ar dating were used early in the history of obsidian studies (e.g., Belluomini et al. 1970; Durrani et al. 1971), and were followed by thermoluminescence characterization (e.g., Leach and Frankhauser 1978). Dates listed in Table 2 were determined by fission track, K/Ar, and by radiocarbon of associated material (Keller 1982, 319).

Glassy materials similar to obsidian

Examples of obsidian-like material are occasionally reported in the archaeological literature, and in some cases may be confused with obsidian. Pitchstone is a glassy rock similar in composition and appearance to obsidian, but containing more water (up to 10%) and typically more devitrified. Despite its rather dull, pitchy lustre, pitchstones were used for blades and other tools in Neolithic Britain, and their distribution from sources on the Island of Arran in Scotland has been studied by Williams-Thorpe and Thorpe (1984).

Tektites, small pieces of probably terrestrial material displaced and melted by impact of extra-terrestrial bodies, have been reported from prehistoric sites in central Europe (summary in Williams and Nandris 1977). These greenish or brownish glassy lumps could be visually confused with obsidian unless ablation features, indicating passage through the earth's atmosphere, are seen. No analyses of tektites from archaeological contexts have been reported, but study of other examples has shown that tektites differ chemically from obsidian (e.g., Thorpe 1978; O'Keefe 1976).

A hand-axe of probably Acheulian age, made of Libyan 'desert glass' is reported by Roe et al. (1982). The origins of desert glass, which has SiO₂ of about 98%, remain a mystery, but it could be an impactite and, therefore, related to tektites. Desert glass, however, is reported in pieces up to 34 cm across, in contrast to the much smaller tektites whose maximum recorded weight is 235 g (Williams and Nandris 1977), implying a piece about 10 x 10 x 1 cm. The colours of desert glass range from clear, through yellow, to green and black, and it is difficult to see how such glass could be visually distinguished from many obsidians.

Volcanic glasses of basic composition, or tachylite (called sideromelane by Cann 1983), rarer than acid vitreous materials, can occasionally form pieces large enough for tool making. Irregular lumps about 2 cm across can be found in Mull (author's observations), as large as many a fragment of pitchstone found in archaeological collections.

OBSIDIAN STUDIES IN ARCHAEOLOGY

The following review is based on over 100 articles and books which meet the criteria for inclusion noted in the 'Introduction'. Conference abstracts and theses are included when the work described has not been published elsewhere.
There have been several other summaries and reviews of obsidian studies, and also many works concerning trade and exchange (referred to later in this review), which draw heavily on obsidian distributions. Both provenancing and hydration layer studies were described within one of the earliest archaeological science texts, edited by Brothwell and Higgs (first published 1963, reprinted from the second edition in 1971), also within Taylor’s (1976) *Advances in obsidian glass studies*, and by Cann (in Kempe and Harvey 1983; this article contains a valuable introduction to geochemical processes affecting obsidian composition). Renfrew and Dixon (1976) reviewed obsidian provenancing in western Asia. The volume on *Method and theory in archaeological obsidian studies* (Shackley forthcoming) is intended to update these works. The present paper is intended to complement these earlier studies, but for completeness will contain some duplication.

Several authors (Cann *et al.* 1971; Cann 1983) have noted early attempts at characterization of stone, and particularly obsidian. Amongst the attributes used for early source recognition were colour (Wace and Thompson 1912); general appearance including presence of white spots (Evans 1921; Evans wrongly assigned Giali obsidian found on Crete to the Lipari source, thus providing an early vindication for later, more sophisticated, provenancing programmes); refractive index and density (Wainwright 1927; Frankfort 1927; Boyer and Robinson 1956; Georgiades 1956); and melting temperature (Castiglioni *et al.* 1963). Early chemical analyses of Central American obsidian sources (Copan, Chichen Itza) were determined by Washington (1921) while major elements were used by Georgiades (1956) to distinguish Aegean sources.

Most of the current information on obsidian distributions has been produced by analytically-based work carried out in the last 30 years or so, sometimes enhanced by statistical data processing, and supplemented by some obsidian dating (fission track, K/Ar, and hydration layer). These studies will be described in order by geographical region, starting with the western Mediterranean and working eastwards through central and eastern Europe and the Aegean, to Anatolia and the Near East. Consideration of trade and exchange studies of obsidian will be discussed following these regional reviews.

Figure 2 shows the locations of obsidian source areas within the region considered (with enlargements of parts of the Carpathian and Near Eastern source areas, in Figs. 3 and 4 respectively), and the sources are detailed in Table 2. Figure 2 also summarizes directions and extent of early obsidian trade. It conflates data from several thousand years (Palaeolithic to Bronze Age) into one distribution and is, therefore, intended to serve only as an introduction to the subject. Further sources of glassy obsidian or obsidian-like material within the Mediterranean and Europe have been noted in Germany, southern France and near Naples (Hallam *et al.* 1976; Buchner 1949), in Spain (Muñoz 1965; Pliny, *Natural History*. xxxvi. paragraphs 197–8), and in central France (Williams-Thorpe *et al.* 1984a). However, none has been shown to be of any archaeological relevance.

Sources of obsidian further afield, in Saudi Arabia, Yemen and Ethiopia are mentioned by Renfrew and Dixon (1976) and by Cann (1983). They are unlikely to be relevant to prehistoric obsidian use in Europe, the Mediterranean and Near East/Anatolia regions, though they were apparently used more locally (cf. Cann and Renfrew 1964; Renfrew and Dixon 1976; Muir and Hivernel 1976). Dixon *et al.* (1968, 46) note later, historic period, use of Ethiopian obsidian, traded in Pharaonic times as far as Turkey.
REGIONAL SUMMARIES

The western Mediterranean area

Within this area, four sources, all on islands, were used in the prehistoric period (Table 2). These are: Lipari, where some obsidian is post-prehistoric in origin but other flows, including the Gabelotto (now largely hidden beneath later eruptions), provided good quality material (Hallam et al. 1976); Sardinia, where obsidian is widespread in the west of the island (Monte Arci) within four main zones, three of which were utilized by prehistoric man (Tykot 1992); the Pontine Islands, within which only Palmarola provides workable obsidian (Hallam et al. 1976; Buchner 1949); and Pantelleria, the well-known source of dark green peralkaline obsidian, where probably three sources were exploited (Francaviglia 1988). In addition, a glassy comendite (i.e., a peralkaline rhyolite poor in normative iron and magnesium minerals) artefact has been reported from a Nuraghic context in Sardinia (Francaviglia 1984, 316), and this probably originated in the comendites of S. Pietro or S. Antioco in south-western Sardinia.

The first analytical provenancing programme for the western Mediterranean area was that of Castiglioni et al. (1962 and 1963). They considered mineral content, specific gravity, effects of heating, and spectrographic analysis (optical emission spectroscopy) for determi-
nation of several major, minor and trace elements. Basing their provenancing mainly on the chemistry, they suggested that Sardinian obsidian was used in northern Italy. Palmarolan in eastern Italy. and Liparian mainly in southern Italy. Pantellerian obsidian was identified in Malta, together with Melian obsidian. Most of their conclusions have been substantiated by other studies, but the presence of Melian obsidian on Malta has not been found by any other worker.

The important study of Cann and Renfrew (1964) followed, in which the use of geochemically incompatible trace elements (Zr, Y, Nb) determined by optical emission spectrometry (OES) allowed distinction between all four of the main western Mediterranean sources. Analyses of artefacts demonstrated the use of Pantellerian and Liparian (not Melian) obsidian in Malta. However, further work (Dixon et al. 1968) agreed with some of Castiglioni’s conclusions, demonstrating the use of Lipari material in southern Italy. Palmarolan in the east and also at Vlasca Jama (near Trieste), and Sardinian obsidian in northern Italy.

The introduction of non-destructive instrumental neutron activation analysis (INAA) to western Mediterranean obsidian studies came in 1976, by workers at Bradford University, U.K. (Hallam et al. 1976). Results served to underline earlier patterns, with Sardinian obsidian in northern Italy. Liparian in the south and east as well as in Sicily and Malta, and in southern France. Patterns of distribution were described in terms of interaction zones (as in Renfrew and Dixon 1976) which were then related to sources by a ‘gravity’ model incorporating factors for source–site distance and on-site quantities of obsidian. The model could be used to deduce relative source ‘attractiveness’ and thence, theoretically (though it has not so far been used in this way) to predict obsidian amounts at specified parts of an interaction zone. Further neutron activation analyses (Williams-Thorpe et al. 1979; Williams-Thorpe et al. 1984a) refined these distributions, extending the Lipari distribution into northern Italy, and suggesting a linked movement of obsidian along the Ligurian coast from Italy to France. Independently, Pantellerian obsidian reached a Copper Age dolmen in France. Spain figured hardly at all in all these studies: only one archaeological piece was reported (Muñoz 1965) and no evidence has been sought for further finds, or sources, in that area.

During the 1970s and 1980s, a number of workers began to test the feasibility of other analytical/physical measurements in obsidian characterization, sometimes overlapping in areas of interest. Longworth and Warren (1979) used non-destructive Mössbauer spectroscopy (nuclear gamma resonance) to determine essentially the ferric/ferrous iron contents of source samples. An early application of discriminant analysis to these data allowed distinction between three out of four sources studied. In 1981 Gale used strontium isotopes to distinguish sources, and in 1983 McDougall et al. presented results of an innovative magnetic study on obsidians, a method which was non-destructive as well as cheap and rapid. Saturation magnetization and mass susceptibility allowed clear distinction between three flows on Lipari, but could not distinguish Sardinian obsidian from these. The more complex technique of inductively-coupled plasma emission spectrometry (ICP, ICPES) refined analyses of Sardinian obsidians (Heyworth et al. 1988). In the same paper the authors showed that major and minor elements can be used as well as traces, when processed by discriminant analysis. Major and minor elements were also used for Mediterranean source discrimination by Francaviglia (1984), though Michels (1982) had found this approach to be less successful in a case study of Guatemalan obsidian.
Meanwhile, regional studies, using conventional INAA and X-ray fluorescence (XRF) techniques served to fill in some detail within the broader distributions provided by the seminal studies of the Cambridge and Bradford teams (e.g., Ammerman 1979; Crummett and Warren 1985; Francaviglia and Piperno 1987; Francaviglia 1988; Gill and Warren 1983; Ammerman et al. 1990). Unpublished analyses from the University of Bradford (by the author Williams-Thorpe, 1976) showed the presence of Pantellerian obsidian in north Africa.

Sardinian sources, first studied by Puxeddu (1958) and later by Mackey and Warren (1983), Aramu et al. (1983) and Herold and Althaus (1987), were, nevertheless, inadequately located and characterized until recent work by Tykot (1992; electron microprobe and ICP analyses forthcoming) which categorized samples from 41 localities into four groups.

Dating of the geological age of obsidians by fission track and K/Ar methods has been used to characterize western Mediterranean sources (Belluomini et al. 1970; Bigazzi et al. 1971; Arias-Radi et al. 1972; Bigazzi and Bonadonna 1973; Belluomini 1973; Bigazzi et al. 1976; Bigazzi and Radi 1981), though little source assignment has actually been done by these methods. One of the most useful studies was that of Bigazzi and Bonadonna (1973) which showed that only one of the three main obsidian flows known on Lipari, the Gabellotto, was old enough to have been the source of prehistoric artefacts. Hydration layer dating has been used, in conjunction with atomic absorption spectroscopy, to characterize obsidian artefacts found in Sardinia (Michels et al. 1984).

From Figure 2 it is evident that Aegean, Anatolian and Near Eastern obsidian was not generally imported to the western Mediterranean. One exceptional intrusion of central European obsidian into an area dominated by western Mediterranean sources is seen at Grotta Tartaruga near Trieste, and Tykot (forthcoming) notes a report of Melian obsidian near Pisa. However, within the western Mediterranean area, source distributions were seen to overlap increasingly as further work was done, and the separate zones of interaction identified by Hallam et al. (1976) now overlap much more.

Central and eastern Europe

Study of obsidian sources in central/eastern Europe (Slovakia, Hungary, Romania, the former U.S.S.R.) has been hampered by practical difficulties resulting from the division of the region by several political boundaries. However, some work has been carried out, and Nandris (1975) has dismissed Romanian sources as unworkable, while Williams and Nandris (1977) described workable obsidian at two source localities in Hungary and obtained glassy material from three sources in eastern Slovakia. Sources in south-western ex-U.S.S.R. remain unexplored by western archaeologists, but are reported as glassy (references in Williams and Nandris 1977). Biró (1984, 43) noted six obsidian sources in north-eastern Hungary and three in eastern Slovakia (Biró 1981, 195). Figure 3 shows the locations of sources of obsidian in north-eastern Hungary and eastern Slovakia.

Hungarian and Slovak obsidian were included in Cann and Renfrew’s 1964 study, but no artefacts were assigned to this area. Other early studies include two fission track dates given by Durrani et al. (1971), and some limited analysis of Tokaj (Hungary) material and artefacts (Milisauskas 1976; Stelcl 1973). Williams-Thorpe et al. (1984b; summary in Williams-Thorpe et al. 1987) analysed 48 source samples and 270 artefacts from central
Figure 3  Map showing the locations of obsidian sources in north-eastern Hungary and eastern Slovakia (compiled from Williams and Vandrés 1977 and Biró 1981). Obsidian at Tokaj consists of nodules up to about 8 mm diameter. The author has not seen source material from Čejkov and Kašov (reported as sources by Biró 1981).

and eastern Europe by INAA, and showed that most came from eastern Slovak sources, with a minority originating in north-eastern Hungary. Hungarian obsidian is generally black and opaque, while Slovak material is grey and translucent; this property can be used to allocate archaeological artefacts to the two source areas, with an estimated error of less than 1%. Williams-Thorpe *et al.* (1984b) used principal components analysis and discriminant analysis of the analytical data to separate source groups and assign artefacts to sources, respectively. It may be noted that this method gave the same results in terms of artefact assignment as cluster analysis applied to the same data (Thorpe 1978), and indeed as simple bi-variate element graphs (Thorpe 1978). Williams-Thorpe *et al.* (1984b) also introduced the concept of a half-distance, defined as the distance within the contact zone (i.e., outside the supply zone within which obsidian forms 80% or more of lithic assemblages; Renfrew *et al.* 1968) at which the percentage of obsidian found at sites is reduced to half its initial value. This concept was used to 'predict' expected amounts of obsidian at given distances from sources, and thus identify sites with 'too much' obsidian
which may, therefore, have acted as secondary distribution centres (cf. also Hallam et al. 1976 discussed above).

ICPES data, processed by discriminant analysis, have been used to distinguish central European sources from other European obsidians (Heyworth et al. 1988). Rasson et al. (1977) used XRF and OES data, enhanced by discriminant analysis followed by Mahalanobis D-squared probabilities of source origin, to assign artefacts from Bosnia mainly to Sardinian source(s). The presence of Sardinian obsidian in southern central Europe has not been confirmed by any other analytical study so far and is at variance with other distributions, as shown on Figure 2. One possible source of confusion is the analytical similarity of Sardinian and southern Anatolian obsidians noted by Rasson et al.; southern Anatolian obsidian has been noted in southern central Europe (Çiftlik source obsidian at Sitagroi, see below).

Much recent work in Hungary has been initiated by Biró. This has included source descriptions (e.g., Biró 1984), chemical analyses of source material by OES (Biró 1981) and energy dispersive (ED) XRF (Biró et al. 1986), and electron microprobe analyses of eastern European sources (Biró and Pozsgai 1984) and also of Mediterranean sources (Biró et al. 1986). In addition, a hydration layer study was carried out, using optical microscopy together with electron microscope and scanning electron microprobe work (Biró and Pozsgai 1982). This successfully distinguished between the two main types of central European obsidian, the generally translucent Carpathian 1 and the more opaque Carpathian 2 (cf. Williams-Thorpe et al. 1984b). (Further references to the work of Biró and colleagues are incorporated in Fig. 5 below.)

Two Hungarian samples of obsidian were included in the fission track dating study of Durrani et al. (1971) in order to exclude a central European origin for artefacts from Franchthi cave in Greece. Some fission track work has been done on central European obsidian (Répégok 1977), and this has been extended to archaeological studies by Bigazzi et al. (1990).

The Aegean area

Obsidian sources in the Aegean used in prehistoric times outcrop on the islands of Melos and Giali. On Melos two localities contain workable obsidian and these were referred to as Adhamas and Dhemenegaki by Renfrew et al. (1965). Later workers refer to the Adhamas source as Sta Nychia (Torrence 1986; Agia Nychia in Francaviglia 1984). Melian obsidian is described as ‘pearly’ in lustre (as opposed to shiny) (Renfrew et al. 1965), and always opaque. Detailed study of the working sites was made by Torrence (1979a, 1982 and 1986). The obsidian source of Giali is described in an unpublished manuscript by Torrence and Cherry (1976), and was noted by Renfrew et al. (1965) as being characterized by whitish spherulites. It appears that Melos provided almost all the obsidian obtained from Aegean sources, with Giali used only for specialized vase and ornament production (Renfrew et al. 1965; Torrence 1986, 94). Spheroidal pieces of obsidian are reported on Antiparos (Renfrew et al. 1965, 232) but there is no evidence for prehistoric use of this less workable material (cf. Francaviglia 1984, 315).

Georgiades (1956) made an early study of Greek obsidians using refractive index and chemical analysis, and this was followed by Castiglioni et al. (1963) who included some Melian obsidian in their provenancing tests. (As noted above, their assignments of artefacts from Malta to a Melos source have not been supported by later work, and are not included
in Fig. 2.) Cann and Renfrew (1964) group Melos with other calc-alkaline obsidians from central Europe. Armenia and Anatolia, and distinctions within this group were established by Renfrew et al. (1965), who determined a distribution from Melos including Crete, the Peloponnese, western and northern Greece. Later provenancing studies of Aegean obsidians extended this distribution to northern and western Anatolia (Dixon et al. 1968) and to north-eastern Greece (Aspinall et al. 1972; see also Aspinall and Feather 1978 and Thorpe 1978. All these are based on INAA). Aegean obsidian is included in the studies of Gale (1981), Francaviglia (1984), McDougall et al. (1983) and Heyworth et al. (1988) (cf. above for methods), but these do not alter the distribution of Melian obsidian. Fission track dating (Durrani et al. 1971) demonstrated that obsidian found at Mesolithic Franchthi cave in Greece originated in Melos. Regional and further studies include Filippakis et al. (1981), Shelford et al. (1982), Evans and Renfrew (1968), and Warren (1978).

The distribution of Melian obsidian is discussed by Renfrew (1972) and, like the western Mediterranean and central European distributions, shows little overlap with surrounding sources (cf. Fig. 2). An exception is the site of Sitagroi where both Melian and Çiftlik (Anatolian) obsidian have been identified (Aspinall et al. 1972). Renfrew et al. also note the presence of probably Anatolian material in Crete (1965, 239). Though at present there is no evidence for overlap of Aegean and Carpathian obsidian source distributions, the area where this might occur, between southern Hungary and the former Yugoslavia, and northern Greece, has been insufficiently studied. Transparent obsidian has been reported at Niš (Renfrew et al. 1965, 237) and may well be Carpathian 1 type.

Anatolia and the Near East

The obsidian sources of Anatolia and the Near East are difficult to understand because of the many different names and terminologies used for the source areas. These include the group numbers and locality names of Renfrew and colleagues, who made early attempts to locate and characterize the sources in this area (Renfrew et al. 1966 and 1968; Renfrew and Dixon 1976): the Hebrew University and Bradford letter and number terminologies (see Blackman 1984); and further locality names introduced by Perlman and Yellin (1980). The source localities have been recently summarized and listed, with analyses, by Gratuzé et al. (1993) and these are taken as the basis for the listing in Table 2.

Sources occur in the Cappadocia area of Anatolia in central Turkey, around Çiftlik and Acigöl, with eight localities listed by Gratuzé et al. (1993, 18). Further east, the Bingöl sources lie in the Taurus mountains of eastern Turkey, and the peralkaline obsidian source of Nemrut Dag volcano is located on the western side of Lake Van. The most problematic area, however, is the Armenian/Van region between Lake Van and Lake Sevan (a distance of about 200 km), within which there are several sources, at Kars, Erevan, Bayezid (Renfrew and Dixon 1976), Sevan and Sarikamis (Gratuze et al. 1993). The Bingöl and Armenian Van sources are located on Figure 4. The Cappadocian sources all lie near to Çiftlik and Acigöl (Gratuze et al. 1993), and can be located as town and village names on a standard 1:800,000 road map of Turkey.

Characterization and provenancing of Anatolian and Near Eastern obsidians was begun by Renfrew and colleagues, with some analyses in 1964 (Cann and Renfrew) and major studies in 1966 and 1968 (Renfrew et al.). Summaries and reviews are in Dixon et al. (1968)
and Renfrew and Dixon (1976). At the same time as these OES studies of Renfrew et al., some of the earliest INAA analyses to be used in obsidian provenancing were being carried out on Near Eastern sources and artefacts (Wright 1969 (this study also includes Mediterranean sources for discrimination); Wright and Gordus 1969a and 1969b; Gordus et al. 1971).

Later studies include magnetic work by McDougall et al. (1983) and Hammo (1985), and regional and source studies of Mahdavi and Bovington (1972), McDaniels (1976), Periman and Yellin (1978 and 1980), Yellin and Perlman (1981), Blackman (1984), Yellin and Garfinkel (1986), Blackman (1986), Cauvin et al. (1986), Yegingil and Lunel (1990), Schneider (1990), Cauvin (1991), and Gratuze et al. (1993, referred to above; this paper describes non-destructive work using fast neutrons and proton induced gamma emission (PIGE) study, but is difficult to compare with other work because it is largely based on element ratios). Fission track dates for some central Turkish obsidians were provided by Durrani et al. (1971) and more recently fission track work was used for provenancing by Yegingil and Lunel (1990).

The research referred to above, summarized on Figure 2, indicates that obsidian from central Turkey (Acigöl and Çiftlik areas) was used in southern Anatolia and in the Levant.
(Israel, ancient Palestine, Syria), also reaching the islands of Cyprus and (in the Minoan period) Crete. Material from the Nemrut Dag and Bingöl sources was used within the Tigris/Euphrates belt, eventually reaching as far as the Persian Gulf, and is also found in the Levant, overlapping Anatolian source use. The more northerly Armenian sources may have had a more restricted distribution. The unexpected presence of Çiftlik area obsidian at Sitagroi in north-eastern Greece was mentioned above (identified by Aspinall et al. 1972). There is, thus, some interaction between Anatolian and other Near Eastern obsidian sources, and also, at the edges of the Anatolian/Near Eastern distributions, with obsidian from Melos and Giali.

TRADE AND EXCHANGE STUDIES

The research on obsidian distributions, particularly in the Near East, led to Renfrew's early ideas about description and thence interpretation of obsidian trade. The relative abundance of obsidian provenance data, and especially the spread of these data over archaeological time, made this region the most appropriate choice for developing these ideas. The concepts of supply zone (within which more than 80% of the lithic assemblage is obsidian; see above) and contact zone (within which obsidian as a proportion of total lithics reduces approximately exponentially over distance) were introduced by Renfrew et al. (1968; Renfrew 1969a; also Dixon et al. 1968). This could be explained by a down-the-line trade or exchange in which each locality within the contact zone kept a proportion of the obsidian it received, and the rest was taken on to the next locality. The ideas of interaction source zones (within which sites derived 30% or more of their obsidian from the same source) and of local redistribution centres for obsidian (to explain non-monotonic fall-off in later (post-5000 BC) movement) were added later (Renfrew and Dixon 1976).

These ideas represented one of the first attempts to explain materials movement, or trade, in terms of numerical data, and formed the platform for considerable later discussion (Renfrew 1975 and 1977a). The basic principles of supply, contact and interaction zones were incorporated in later obsidian provenancing studies (Hallam et al. 1976; Williams-Thorpe et al. 1984b), and consideration of obsidian trade mechanisms has been applied to regional study in some areas (e.g., Ammerman 1982; Ammerman et al. 1978). Obsidian distributions were also incorporated in the concept of using a numerical value (alpha) to describe mathematically either a steep fall-off of goods with distance from source (low alphas, locally-moved goods) or shallow fall-off (high alphas, further moved goods) (Hodder 1974; Hodder and Orton 1976). Alphas used in this way also have implications for the size of the production centre.

A non-mathematical, ethnographic, approach was taken by Crawford (1978) in which it was suggested that, in the absence of proof of reciprocity of goods in a down-the-line situation, the movement of obsidian might rather have been due to long-distance migration of nomadic peoples.

Figure 2 gives an overview of obsidian movement, through trade or other human processes, in the prehistoric periods within the areas considered here. As noted above, it is a conflation of data from the Palaeolithic to Bronze Age periods, although much, probably the majority, of the information stems from Neolithic contexts. Two points emerge: first, the enormous amount of information represented here, indicating contacts of which we had no proof, and in some cases no idea, prior to the obsidian provenancing
programmes—a reminder that obsidian provenancing has been a success story for archaeology as well as archaeometry. Second, although obsidian finds represent evidence for long-distance cultural contact and movement of resources (up to about 900 km in some cases), the impression from Figure 2 is actually one of self-contained, non-overlapping exchange regions, based on the four areas discussed in this review. Whether due to the tailing off of down-the-line type exchange networks or to the limits of nomad travel (or to other unknown factors of political or economic constraints), these obsidian transport zones rarely interacted. The limits on these zones must have had implications for the dissemination of other materials (and ideas) spread with obsidian; the obsidian itself may not have been the only, or even the major, object of the trade (cf., e.g., Renfrew 1969a, 159; Renfrew et al. 1966, 50).

This picture of separate exchange zones also serves as a reminder that our complexities of interpretation are imposed on slow and primitive systems of human transport. It would be interesting to determine the time lapse between obsidian procurement at a source and its arrival at the end-of-the-line findspot. Precision of dating may be insufficient to do this, but the time-scale could have been of the order of generations.

DISCUSSION

Figure 5 (a) shows the frequency of publications dealing with obsidian research relevant to provenancing, over a period of about 40 years. It is based on 111 papers, including reviews and chapters in books, which conform to the criteria stated at the beginning of this review. The sudden increase in popularity of obsidian provenancing in the late 1960s and early 1970s, following the early successes of Cann, Renfrew, and Dixon, is clear. Numbers of papers increase up to 1976, remain fairly steady till the mid-1980s, and have declined somewhat, on average, in recent years. The western Mediterranean area has gained most attention (Fig. 5 (b)), followed in order by Anatolia and the Near East, central and eastern Europe, and then the Aegean.

The subject was, of course, so popular, because obsidian provenancing is relatively straightforward. This is not in any way to undervalue the work done, in particular the early innovative and seminal studies, and those which more recently have concentrated on understanding complex source areas such as Sardinia or Armenia. However, the limited number of sources and in particular the young, fresh and homogeneous nature of this geologically rare material make chemical analysis likely to be reliable and discriminating. Geologically more common rocks, older rocks and coarser-grained materials are likely to present progressively greater problems in terms of frequency of sources, chemical alteration, and the size of sample required for representative analysis. Thus, rhyolites and basalts, for example, will be more difficult to characterize than obsidians, while coarse-grained igneous rocks such as granitoids will present even greater difficulties. Obsidian offered an ideal training ground for archaeological provenancing, and it is due to the perspicacity of early workers that it was recognized and chosen as such.

The decrease of papers in recent years is probably a reflection of several factors: first, the basic distributions are now established and it becomes rather less exciting to simply ‘fill in the gaps’. Second, archaeological science has become increasingly focused on environmental and biochemical studies in recent years; in such a climate, lithic studies may gain less attention. And third, it is probably simply a reflection of fashion: obsidian research was a
Figure 5  Histograms showing (a) the frequency of publications on archaeological obsidian research in the area under review, between 1955 and the present, (b) the frequency of publications dealing with specific geographical areas (not including review papers), and (c) the choice of analytical techniques in publications ('others' includes study by: isotope analysis, magnetism, Mössbauer analysis, microprobe, atomic absorption analysis, specific gravity, refractive index, PIGE, ICP-ES and petrographic thin section). Papers included in each histogram are listed in the Appendix.
bandwagon on which many workers (including the present author) jumped with enthusiasm, but it has now lost its initial momentum.

The increase and now fall-off of archaeological obsidian research papers conforms to a well-established pattern of scientific research, reflecting the initial recognition of a problem, the increasing input to problem solving, followed by the decline in scientific attention as approaches (and interest?) are exhausted (pers. comm. anonymous referee; Crane 1972).

The pattern shown in Figure 5 (a) is not, however, what we might wish to see in a provenancing research programme. For a given artefact/rock type, initial studies should increase over time as various techniques are tried, until a reliable basis of provenancing is established, and basic distribution work done. After this, the number of applications and reports should increase rapidly and remain at a high level, as the chosen technique(s) are applied routinely to appropriate proportions of the artefact at excavated sites and collections. Perhaps such a pattern is not reflected in Figure 5 (a) because such routine applications are attached to site reports and do not appear in the archaeological science literature reviewed here? Possible, but unlikely. More likely that lack of a financial framework for routine analysis in many areas covered in this review means that it is, in the main, not done.

Developing a provenancing basis for obsidian (and other artefacts) produces an initial data base of results which remains valuable. However, a further aim of the development is that provenancing should become a routine part of post-excavation work. Without this, much of the point is lost and there is a danger of such work becoming rather self-indulgent, albeit extremely enjoyable, research exercises by archaeological scientists.

The choice of techniques in obsidian provenancing is reflected in Figure 5 (c). While in theory such choice should be a reasoned decision based on which method is most appropriate to the rock or artefact type, in practice it is more often a combination of what is available to the researcher, and of trying anything that might work. The two dominant techniques, OES and INAA, are highlighted. Despite its ubiquity in geological analysis work, XRF (also noted on Figure 5 (c)) has been little used in obsidian study, probably because of the relatively large sample required for many XRF procedures. Other techniques—including magnetic studies, PIGE, electron microscopy, Mössbauer spectroscopy—also remain in the minority. While many different techniques were tried within the context of rapid equipment development in the 1970s and 1980s, INAA, a largely non-destructive technique, emerged as the most popular technique by the early 1980s.

Other non-destructive techniques include magnetic study (McDougall et al. 1983), and measurement of natural (beta) radiation, developed at Bradford University for the discrimination of New Zealand obsidians (Leach et al. 1978; cf. Leach and Warren 1981). Magnetic study proved to be less successful than trace element chemistry in discriminating sources, but could, nevertheless, provide a very useful first screening method. Natural radiation measurement has not been applied to the area under review, but might provide an equally useful first assessment, particularly between obsidians of peralkaline and alkaline or calc-alkaline type. Both methods are cheap and easy to do, and, used in conjunction with trace element analysis of selected samples, might provide an accessible form of routine provenancing. A recent description of high-precision non-destructive energy-dispersive XRF for obsidian provenancing (Giauque et al. 1993) also offers a likely alternative to INAA. Back-scattered electron (BSE) imaging, used success-
fully in the U.S.A. for obsidian characterization, is also essentially non-destructive, though it requires polishing of an area of c. 1 cm x 1 cm (Burton and Krinsley 1987).

The development of new mercuric iodide crystals for high-resolution detection in field portable EDXRF systems (Potts et al. 1995; Cesareo et al. 1992) also provides a promising non-destructive method. Obsidian, with its glassy texture and chemical homogeneity, would provide an eminently suitable material for this method. Critical penetration depths in silicate rocks for the X-rays measured by portable EDXRF are between 0.004 and 8.2 mm. Therefore, surface corrosion (hydration) of obsidian, measured in terms of µg (e.g., 2–5 µg per 1000 years in the U.S.A., Ericson 1988), may sometimes affect some elements such as Na, but elements producing higher energy X-rays would not be affected. Potts et al. (1995) have shown that portable XRF can give precision of 1–5% relative standard deviation for prepared surfaces, thus approaching the precision of laboratory-based techniques for some elements. It is noteworthy that the use of non-destructive field portable techniques in other provenancing areas, such as Roman granitoid columns, has increased the number of artefacts available for study by a factor of about ten (cf. Williams-Thorpe and Thorpe 1993).

It may now be possible to assess which analytical method(s) have been the most effective in obsidian work. Table 3 gives a summary of techniques used in the area under review, together with comments on their effectiveness and degree of destructiveness. A chart of techniques available for stone artefact study is given in Kempe and Harvey (1983, 27), and some methods used for obsidian outside the area reviewed here are noted in Thorpe (1978).

In terms of effectiveness of source discrimination, it became clear early in the history of obsidian studies that physical characteristics such as colour, texture, refractive index, and specific gravity were insufficiently diagnostic. Later work confirmed that chemical composition, and in particular trace element composition, is the most effective discriminant. Although OES provided the first chemical data base for obsidian studies, poor precision in that method has led to its being largely replaced in silicate rock analysis by XRF, ICPES and INAA. All these methods have the capability of precise and sensitive analysis of trace elements (including geochemically diagnostic and stable elements such as Zr, Nb, Y, and some rare-earth elements). Existing published data bases appear most extensive for INAA. INAA, XRF and ICPES have all been used for Mediterranean source discrimination (Hallam et al. 1976; Francaviglia 1984; Heyworth et al. 1988), and this provides an opportunity to compare the practical effectiveness of the techniques. INAA using concentrations of La and Cs normalized to Sc (Hallam et al. 1976, 96) allows very clear discrimination of four sources, with tight groupings and no overlaps. The distinction remains even when archaeological samples from several Sardinian sources are added. XRF trace element data (Francaviglia 1984, tables 1–2) provide clear distinction between Pantelleria, Palmarola and Lipari. Sardinia is closer compositionally to the other sources, because of the wide spread of analyses from this island’s several sources, but may still be distinguished by using differences in Sr and Cl and to a lesser extent Rb. Discrimination is not as clear as with INAA elements. Major elements, also analysed by Francaviglia (1984), do not give unambiguous source discrimination (Francaviglia 1984, 330). ICPES approaches INAA in clarity of source distinction (though it provides less analytical distance between Palmarola and Lipari) (Heyworth et al. 1988, 32), but the use of statistics makes the data much less accessible to later workers. Simple ratios as used by Hallam and co-workers offer immediate data comparison.
<table>
<thead>
<tr>
<th>Method of provenancing</th>
<th>Important references</th>
<th>Comments</th>
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<tbody>
<tr>
<td>Mineral content</td>
<td>Cann and Renfrew 1964</td>
<td>Not diagnostic of all sources</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>Cann and Renfrew 1964</td>
<td>Destructive</td>
</tr>
<tr>
<td>Refractive index</td>
<td>Castiglioni et al. 1962 and 1963</td>
<td>Very small sample required, but has poor precision. Now little used in silicate rock analysis</td>
</tr>
<tr>
<td>Heating/melting properties</td>
<td>Castiglioni et al. 1962 and 1963</td>
<td>Very successful: no crushing or sub-sampling needed; can analyse whole samples; very good precision and very diagnostic; however, samples are radioactive and INAA may alter characteristics, e.g., luminescence</td>
</tr>
<tr>
<td>Optical emission spectroscopy (OES)</td>
<td>Cann and Renfrew 1964; Renfrew et al. 1966; Castiglioni et al. 1962 and 1963</td>
<td>Successfully characterizes some Near-Eastern sources; non-destructive as INAA</td>
</tr>
<tr>
<td>Proton induced gamma emission spectroscopy (PIGE)</td>
<td>Gratuzè et al. 1993</td>
<td>Trace elements mainly diagnostic of sources, but some problems: e.g., Lipari and Sardinia difficult to distinguish; relatively large sample needed for WDXRF, up to several g. Generally destructive, but EDXRF can be non-destructive</td>
</tr>
<tr>
<td>X-ray fluorescence analysis major and trace elements (WDXRF and EDXRF)</td>
<td>Francaviglia 1984; Giauque et al. 1993</td>
<td>Successful but no advantages over INAA; small sample required</td>
</tr>
<tr>
<td>Strontium isotopes</td>
<td>Gale 1981</td>
<td>Successful, needs small sample, represents modern development of OES; advantages are that many elements are determined (major and trace) (but traces generally sufficient for obsidian characterization)</td>
</tr>
<tr>
<td>Inductively coupled plasma emission spectroscopy (ICPES)</td>
<td>Heyworth et al. 1988</td>
<td>Useful for central Europe sources but not used elsewhere in the Mediterranean and surroundings; so no data base for most sources. Sample preparation needed but sample not destroyed</td>
</tr>
<tr>
<td>Electron microscopy, electron microprobe analysis (EPMA)</td>
<td>Biró and Pozsgai 1982 and 1984</td>
<td>Non-destructive; not all sources distinguished</td>
</tr>
<tr>
<td>Mössbauer spectroscopy</td>
<td>Longworth and Warren 1979</td>
<td>Non-destructive; not all sources distinguished</td>
</tr>
<tr>
<td>Magnetic properties</td>
<td>McDougall et al. 1983</td>
<td>Useful in early days of obsidian work; little used now in obsidian work; sample required</td>
</tr>
<tr>
<td>Geological dating methods: K/Ar, fission track</td>
<td>Durrani et al. 1971; Bigazzi et al. 1990</td>
<td>Requires sample preparation; difficulty in establishing rates of hydration for different areas, therefore unlikely to be widely applicable</td>
</tr>
<tr>
<td>Hydration layer dating</td>
<td>Michels et al. 1984; Biró and Pozsgai 1982</td>
<td></td>
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</table>
Sample size required is also an important consideration in archaeological work. OES and ICPES require destruction of a small sample (mg size). Most XRF techniques require a sample of the order of grams. INAA can be carried out on a sample of mg without visible alteration to the sample. However, the radioactivity induced in the sample dictates its storage in a controlled area (i.e., a radiation store, away from people) for typically at least a year, the length of time depending mainly on sample size. In addition it was pointed out to the author (anonymous referee pers. comm.) that INAA is not strictly non-destructive since it may lead to changes in physical characteristics such as luminescence and magnetism of the sample.

Although obsidian is, compared with most igneous rocks, extremely homogeneous, analysis of extremely small, mg sized, samples will, nonetheless, reflect minor and small-scale compositional variations in the rock or artefact, leading in practice to scatter on analytical groups or, in rare cases, to anomalous analysis.

INAA combines high sensitivity, good precision and accuracy, effective discrimination, independence of homogeneity problems (when the whole artefact is analysed), and a largely non-destructive nature, with a well-established data base for this method. For these reasons it can be identified as the preferred technique. However, the case for the development of further non-destructive methods remains strong, in order to obviate the problem of residual radioactivity in INAA. Field portable EDXRF is a most promising technique in this area.

Obsidian studies in the area under review have become rather static. Several areas of progress may be suggested: first, resolving remaining problems in location and chemical composition of sources in the Near East, in the south-western ex-U.S.S.R. and in Sardinia; second, increasing knowledge of Palaeolithic and Mesolithic obsidian movement; third, the development of non-destructive techniques to increase access to artefacts; and fourth, the routine application of INAA and other techniques to artefact assemblages.

CONCLUSIONS

Obsidian is a near ideal rock type for archaeological provenancing, and research on this subject has been extremely successful. Thanks to 30 years of work, obsidian has become one of the best understood examples of lithic procurement in Mediterranean and European prehistory. Studies have shown mainly separate distributions within each of the four regions discussed here—western Mediterranean, central and eastern Europe, the Aegean, and Anatolia and the Near East—with obsidian being moved over distances of up to 900 km. The fact that provenances determined in more recent years generally fit into early-established distributions increases confidence in the robustness of the early data. We, therefore, have a good regional understanding of obsidian source distributions in the areas discussed above, some insight into changing patterns of interaction over time, and a selection of data bases from proven methods of analysis. Problems remain, including the clarification of sources in the Near East and in Sardinia.

Significantly, obsidian provenance research gave rise to the discipline of obsidian trade and exchange studies, which developed concurrently with the interpretation of trade in other prehistoric and early historic artefacts, such as stone axes and pottery.

INAA is identified as an extremely effective and well-used technique for obsidian provenancing, and the need for further non-destructive methods of analysis and characterization, to increase access to artefact assemblages, is noted.
In order to realize the full potential of developing artefact provenancing programmes, it is important that a framework be developed for routine post-excavation analysis work.

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APPENDIX

