and timing of their association with mare basalts; and their styles of eruption, and (4) evaluate the implications of these data for interpretation of lunar volcanic and thermal history. In this paper, the third of these topics is addressed, and a compositional analysis of 18 pyroclastic deposits (15 small and three large) using multispectral data from the Clementine UVVIS (415- to 1000-nm wavelengths) camera is presented.

### 1.1. Characteristics and Distribution of Lunar Pyroclastic Deposits

More than 85 lunar pyroclastic deposits are recognized [e.g., *Gaddis et al.*, 1985; *Hawke et al.*, 1990; *Gaddis et al.*, 1998; Figures 1a and 1b], and numerous additional "dark-mantled" areas have been identified as possible pyroclastic deposits [e.g., *Blewett et al.*, 1995a, b; *Yingst and Head*, 1998]. Lunar pyroclastic deposits are dark and smooth-surfaced, and they are commonly observed in association with sinuous rilles, irregular depressions, or endogenic craters within highlands and/or the floors of old impact craters situated along the margins of many mare-filled impact basins on the lunar near and far sides [e.g., *Head*, 1974]. Previous analyses recognized that many lunar pyroclastic deposits contain dark, glass-rich, friable materials such as those collected at Taurus-Littrow during Apollo 17 [e.g., *Lucchitta*, 1973]. Studies of the orange and black spheres from Apollo 17 samples revealed volatile-enriched coatings, which were inferred to have resulted from fire fountaining during the emplacement of associated mare basalts [e.g., *Heiken et al.*, 1974]. The primitive composition of the pyroclastic glasses indicates that they have undergone little or no fractionation or contamination after leaving their source region, and thus they are inferred to reflect the primary compositional characteristics of the deep (>300-km) interior or mantle of the Moon [e.g., *Delano and Livi*, 1981; *Papike et al.*, 1998]. Compositional analyses of several of the "black spots" from Earth-based spectral reflectance data identified the black spheres as the dominant component [e.g., *Pieters et al.*, 1973, 1974].

Lunar pyroclastic deposits are divided into two classes on the basis of size, morphology, and occurrence [e.g., *Gaddis et al.*, 1985]. The large deposits (~10 in number) are of regional extent (generally >2500 $km^2$ in size), while small deposits (~90 in number) are more localized (<2500 $km^2$). Several large pyroclastic deposits (e.g., those at Taurus-Littrow, Sulpicius Gallus, Sinus Aestuum, and Aristarchus) are observed in the highlands on the margins of several mare-filled impact basins and thus were inferred to mark the locations of source vents for associated pyroclastic and mare volcanic activity [*Head*, 1974]. A range of compositions of these large or regional lunar pyroclastic deposits has been inferred from remote-sensing data [e.g., *Gaddis et al.*, 1985; *Lucey et al.*, 1986; *Hawke et al.*, 1991; *Bussey and Spudis*, 1997; *Weitz et al.*, 1998], with iron-rich volcanic beads (both vitreous and crystalline) inferred to be a spectrally dominant component. Eruption and emplacement of regional pyroclastic materials are thought to have been due to strombolian-style, fire-fountain events associated with high-effusion-rate, long-duration eruptions such as those often associated with large vents and sinuous *rilles [Wilson and Head*, 1981; *Weitz et al.*, 1998]. Such eruptions are thought to have occurred primarily during an early period of lunar volcanism (~3.6 b.y. ago) and to have been favored at impact basin margins by relatively thin crust and extensional stresses [e.g., *Head and Wilson*, 1992; *Lucey et al.*, 1994].

The small, localized pyroclastic deposits such as those along fractures in the floor of the crater Alphonsus are widely distributed across the lunar near and far side [e.g., *Gaddis et al.*, 1985; *Hawke et al.*, 1989; *Coombs and Hawke*, 1988; *Coombs et al.*, 1988, 1990; *Gaddis et al.*, 1997b]. Examples of small pyroclastic deposits found on the far side include those in the floor of Schrödinger crater [*Shoemaker et al.*, 1994], at Oppenheimer crater [*Morrison and Bussey*, 1997; *Rosanova et al.*, 1998], and in the Apollo basin within the South Pole/Aitken Basin [*Robinson et al.*, 1996]. These "dark-halo crater" deposits are interpreted to be the result of vulcanian-style or possibly intermittent eruptions, with explosive decompression and removal of a plug of lava or cap rock within a conduit and formation of a vent crater [*Head and Wilson*, 1979]. In addition to their common occurrence as endogenic dark-halo craters along fractures in Imbrian to pre-Imbrian (>3.2 b.y.) impact craters in highland areas along the perimeters of major lunar maria, localized pyroclastic deposits have been identified as isolated, small, dark materials in highland and maria areas, often with no observable source vent [e.g., *Hawke et al.*, 1989]. Although eruptions of localized pyroclastic deposits are thought to have occurred primarily during an early period of lunar volcanism and to have been favored by relatively thin crust associated with impact basins [see *Head and Wilson*, 1992], a possible "young" (~1 b.y.) deposit has been identified near Taruntius crater (5.2°N, 46.5°E [*Spudis*, 1989]).

As with the regional deposits, a wide range of compositional variation exists among localized pyroclastics. However, instead of new or juvenile volcanic glasses being the spectrally dominant compositional component in the small pyroclastic deposits, identifiable differences in the relative amounts of possible juvenile materials versus host rock form at least three classes of localized deposits (Table 1) [*Coombs and Hawke*, 1988; *Coombs et al.*, 1988, 1990; *Hawke et al.*, 1989]. The juvenile materials may consist of disrupted fragments of a preexisting basaltic cap rock or new magmatic materials from depth. The small pyroclastic deposits were subdivided into three compositional classes on the basis of the depth (i.e., strength), position, and shape of their "1.0-micron" or mafic absorption band in Earth-based spectra [e.g., *Hawke et al.*, 1989] (Figure 2). The mafic absorption band in lunar soils is primarily due to $Fe^{2+}$ in iron-bearing components such as the minerals pyroxene and olivine and the volcanic glasses [e.g., see *Pieters and Englert*, 1993, chap. 14].

**1.1.1. Small pyroclastic deposits: Group 1.** Mafic bands of small pyroclastic deposits in the Group 1 class (Table 1) are centered near 0.94 µm, have relatively shallow depths, and are asymmetrical, with "checkmark"-like shapes (straight, steep short-wavelength edges and shallow, straight long-wavelength edges). Spectra for Group 1 deposits resemble those of typical highlands and are indicative of the presence of feldspar-bearing mafic assemblages dominated by orthopyroxene. Also, the shapes of the mafic bands of Group 1 deposits indicate the presence of an additional iron-bearing component with a band near 1.0 µm (such as volcanic glass, olivine, or clinopyroxene) which has acted to modify the typical orthopyroxene mafic band. Although compositional variation is observed within different Group 1 deposits, most appear to be mixtures of highlands-rich country rock and