Asteroid 3628 Božněmcová: Covered with angrite-like basalts?

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Abstract–A detailed analysis of the reflectance spectrum of asteroid 3628 Božněmcová, previously identified as a possible ordinary chondrite parent body, indicates that its surface consists of an assemblage dominated by clinopyroxene and plagioclase feldspar. The clinopyroxene is Fe^{2+}-bearing (likely in the range $Fs_{\sim10-20}$), with >90% of the Fe^{2+} being present in the M1 crystallographic site (spectral type A). The clinopyroxene:plagioclase feldspar ratio is between ~2 and 3 (~55–75% clinopyroxene, ~20–33% plagioclase feldspar). If olivine is present, the clinopyroxene:olivine ratio is >~3 (<20% olivine). The derived mineralogy of Božněmcová is most similar, but not identical, to the known angrite meteorites. The data suggest that Božněmcová formed by melting and differentiation of an oxidized chondritic precursor and probably represents an unsampled angrite-like body.

INTRODUCTION

Main Belt and near-Earth asteroids represent a diverse suite of objects that provide important insights into the conditions prevalent in the early solar system as well as subsequent modification processes. Forging links between Main Belt asteroids, near-Earth asteroids, and meteorites enables us to reconstruct dynamic and petrogenetic processes operating in the inner part of the solar system. Among the groups of meteorites for which an asteroidal source has yet to be identified, angrites may be the most interesting. These meteorites appear to have formed by melting and differentiation under relatively oxidizing conditions, and record the oldest crystallization ages among differentiated meteorites (Mittlefehldt et al. 1998). Thus, identifying parent bodies for these meteorites can provide important constraints on both the timing of differentiation and the extent of oxidation in the asteroid belt during the early history of the solar system.

Asteroid 3628 Božněmcová was first spectrally characterized (0.5–1.0 μm) during observing opportunities in 1991–1993 (Binzel et al. 1993). Over this limited spectral range, it was found to exhibit similarities to ordinary chondrites, specifically the L6 or LL6 groups, and was assigned to the new O class. Subsequent observations undertaken in 1998–2000 across a wider wavelength range (0.35–1.65 μm) found that the spectral similarity did not continue over longer wavelengths, and a new link to clinopyroxene (augite) was suggested (Burbine 2000; Binzel et al. 2001), although significant spectral mismatches remained. The unusual nature of Božněmcová was also noted in subsequent studies, but no refined mineralogical assignments were proposed (Burbine and Binzel 2002; Bus and Binzel 2002). We have undertaken a more detailed and extensive examination of the Binzel et al. (2001) spectrum of this asteroid, as well as of plausible meteorite and mineral analogues, in order to better constrain its mineralogy, meteorite affinities, and genesis.

EXPERIMENTAL PROCEDURE

In order to constrain the surface mineralogy of Božněmcová, the most complete spectral coverage of this asteroid (0.35–1.65 μm) (Binzel et al. 2001) was used in an extensive comparison with existing and new laboratory mineral reflectance spectra. Spectra included in this study include those measured at the NASA-supported multi-user RELAB facility at Brown University (Pieters 1983) as well as our new facility (HOSERLab) at the University of Winnipeg (Cloutis et al. 2006). Minerals in this database have been

characterized spectrally, compositionally (by X-ray fluorescence and/or electron microprobe, and by wet chemistry), and structurally (by X-ray diffraction). Details of the analytical techniques and sample preparation procedures can be found in Cloutis and Gaffey (1991) and Cloutis (2002). Powdered mineral samples were prepared by hand crushing the samples in an alumina mortar and pestle. Impurities were removed through a combination of magnetic separation, and hand-picking under a binocular microscope. Restricted size fractions were prepared by dry sieving; this was enhanced by lightly brushing the samples in the sieves with an artist's brush.

The RELAB spectra were measured at i = 0°, e = 30° relative to halon at 5 nm resolution. Reflectance spectra acquired at HOSERLab were measured using an Analytical Spectral Devices (ASD) FieldSpec Pro FR Hi-Resolution spectrometer across the 0.35–2.5 μm range. The spectral resolution of this instrument varies from 3 nm at 0.7 μm, 6 nm at 1.4 μm, and 7 nm at 2.15 μm. The spectral sampling interval is 1 nm for the entire 0.35–2.5 μm interval. Measurements were made of dark current, the reflectance standard (a calibrated Spectralon disk), and the powdered mineral samples. The spectra were corrected for minor irregularities in the absolute reflectance of the Spectralon in the 2–2.5 μm region. Wavelength calibration was maintained by measurements of various rare earth standards (DyO, ErO, HoO). Spectral measurements of the reflectance standard, dark current, and samples each consisted of an average of 2000 17 ms scans. Sample illumination was provided by an ASD Fiberoptic Illuminator.

The powdered samples were poured into circular sample holders 10 mm in diameter and 4 mm in depth and then lightly tamped. The sample surface was smoothed by drawing a glass slide across it. These spectra were measured with an ASD Pro Reflectance Probe bifurcated fiber optic bundle that intersperses 78 illumination and 78 detection fibers in a bundle 4 mm in diameter. The field of view of the fiber bundle is 25°, and at the working distance of 10 mm, images a circular region ~5 mm across. Thus, these spectra are measured in near-normal incidence. Because of the design of the optical train, the three detectors do not view exactly the same portion of the sample. Consequently, some of the spectra were corrected for minor offsets at the wavelengths where the detectors change over (1.000 and 1.830 μm). The 0.350–1.000 and 1.830–2.500 μm regions were referenced to the 1.000–1.830 μm range detector by applying a multiplicative factor to the 0.350–1.000 and 1.830–2.500 μm data based on the ratio of the reflectance values at the two crossover points (1.000–1.001 and 1.830–1.831 μm). Because absorption bands in the 1 μm region of many type A clinopyroxenes and in the spectrum of Božněmcová are broad and shallow, our determination of absorption band positions was limited to a visually determined minimum position or the point of most abrupt

slope change. The quality of the asteroid data in particular did not justify a more rigorous approach. As is discussed below, the major mineral that accounts for the major absorption band in the spectrum of Božněmcová appears to be insensitive to compositional variations, and thus a detailed fitting of the absorption bands would not yield additional useful information beyond that which could be derived from visual examination. Both the RELAB and HOSERLab data were resampled to the available band centers of the Božněmcová spectrum.

RESULTS

The reflectance spectrum of Božněmcová was analyzed in relation to single minerals and mineral mixtures. These results were then compared to the spectral and compositional properties of plausible candidate meteorites to determine whether Božněmcová's inferred surface mineralogy is represented in the meteorite collection. The analysis is based on the positions of apparent absorption bands in the spectrum of Božněmcová (~0.95 and 1.15 μm). The quality of the observational data for Božněmcová preclude a more precise assignment of band positions (data coverage in this wavelength region is somewhat sparse compared to other regions) (Fig. 1), but as described below, interpretation of the mineralogy of this asteroid is not critically dependent on absorption band wavelength positions.

One possibility is that the spectrum of Božněmcová is saturated in the 1 μm region. The lack of albedo information for this asteroid does not allow us to state definitively that the spectrum is not saturated in the 1 μm region. However, as discussed below, the candidate minerals that are used to interpret the asteroid's spectrum are generally bright and do not saturate unless average grain size exceeds ~100 μm. In addition, the width of the absorption band in the 1 μm region is less than that for unsaturated component minerals.

Comparison to Clinopyroxene Spectra

The spectrum of asteroid 3628 Božněmcová is characterized by a bowl-shaped absorption feature in the 1 μm region (Fig. 1). An extensive search of laboratory reflectance spectra of minerals and meteorites indicates that Božněmcová's spectrum is most closely matched, to first order, by high-calcium pyroxene, specifically spectral type A clinopyroxene (Adams 1974), broadly consistent with the link to augite made by Burbine (2000). Type A clinopyroxene spectra possess two major overlapping absorption bands near 0.95 and 1.15 μm attributable to crystal field transitions in Fe^{2+} located in the M1 crystallographic site. In contrast, spectral type B clinopyroxenes are characterized by two major absorption bands located near 1 and 2.2 μm that are attributable to crystal field transitions in Fe^{2+} located in the M2 crystallographic site (Fig. 2).
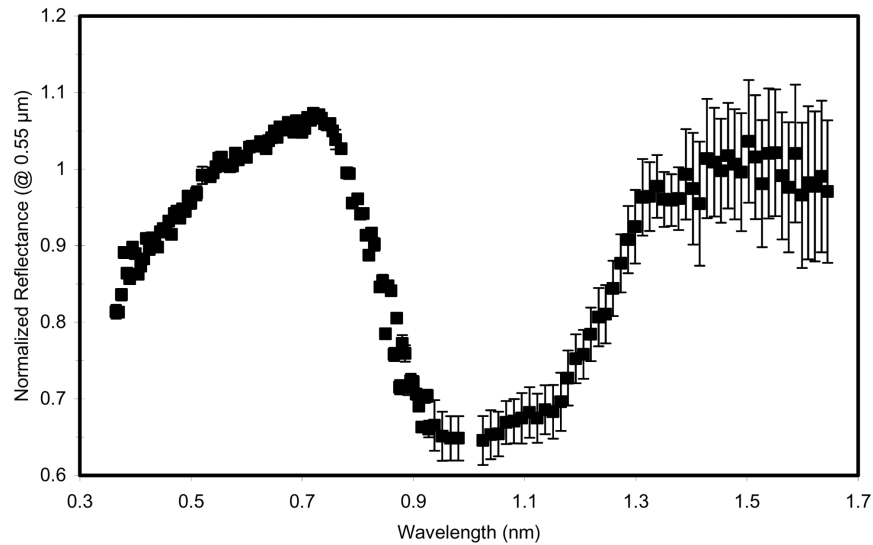
Fig. 1. Reflectance spectrum of Božněmcová (0.35–1.65 μm), normalized to 1 at 0.55 μm (from Binzel et al. 2001). The broad absorption feature in the 1 μm region is the most distinguishing feature of this asteroid.
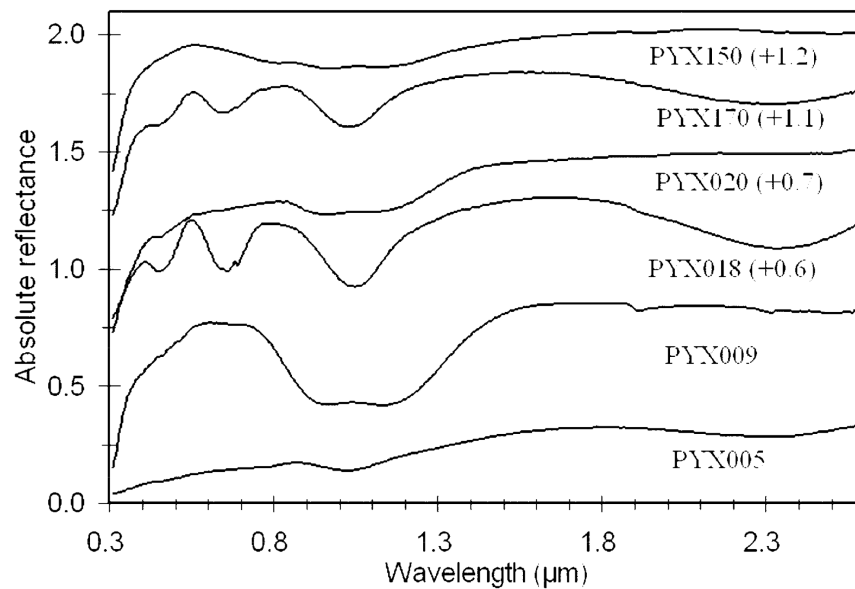

Fig. 2. RELAB laboratory reflectance spectra (0.3–2.6 μm) of three pairs of type A and type B clinopyroxenes. Each pair (PYX005-PYX009, PYX018-PYX020, and PYX150-PYX170) is characterized by very similar compositions (see Table 1). Small variations in composition can lead to significant spectral changes. The value of linear vertical offsets applied to some spectra for clarity are indicated in brackets.

A number of cations strongly partition into the M2 site (e.g., Ca, Na, Co, Zn, Cr, Mn). Any deficiencies in M2 site occupancy by these cations can be made up by Fe^{2+} (Cloutis 2002; Schade et al. 2004). Spectral types intermediate between types A and B are also possible when Fe^{2+} occupies both the M1 and M2 sites (Schade et al. 2004). Such spectra are characterized by a more complex feature in the 0.95–1.2 μm region, and weak or nearly nonexistent absorption bands in the 2.2–2.4 μm region (Schade et al. 2004).

Compositionally, spectral type B clinopyroxenes contain some Fe^{2+} in the M2 site because they do not contain enough cations that strongly partition into the M2 site to fully occupy this site to the exclusion of Fe^{2+}. Spectral type A clinopyroxenes exclude Fe^{2+} from the M2 site. Determining whether spectral type A or B clinopyroxene is present therefore provides information on Fe^{2+} site occupancies. Wavelength coverage up to ~1.7 μm, as is available for Božněmcová, can be used to distinguish between spectral type A- or B-dominated clinopyroxene. As the M2 site is more distorted than the M1 site, absorption bands due to Fe^{2+} located in the M2 site are more intense than M1 Fe^{2+} absorption bands for a given Fe^{2+} content, by approximately a

Table 1. Compositions of terrestrial pyroxenes used in this study.

Oxide (wt%)	PYX005 Type B	PYX009 Type A	PYX018 Type B	PYX020 Type A	PYX150 Type A	PYX170 Type B
SiO_2	49.70	53.90	55.17	55.23	55.75	52.49
Al_2O_3	4.12	0.51	0.37	0.59	0.24	4.48
FeO	5.93	6.20	2.42	2.07	2.56	2.62
Fe_2O_3	0.77	0.00	0.00	0.00	0.00	0.34
MgO	13.80	14.18	17.01	17.06	16.26	15.28
CaO	22.94	25.08	23.93	24.08	25.70	22.47
Na_2O	0.57	0.05	0.51	0.52	0.05	n.d.
TiO_2	1.48	0.01	<0.01	0.09	0.00	0.04
Cr_2O_3	0.17	0.04	0.91	0.96	<0.01	0.99
V_2O_5	0.00	0.02	0.03	0.05	0.00	0.16
CoO	0.04	0.05	0.02	0.05	0.05	0.00
NiO	0.04	0.15	0.07	0.06	<0.01	0.20
MnO	0.11	0.26	0.10	0.10	0.11	0.00
ZnO	n.d.	n.d.	n.d.	n.d.	0.03	0.00
Total	99.67	100.45	100.54	100.86	100.72	99.07
Fs	9.9	9.7	3.8	3.3	4.0	4.5
En	41.0	39.8	47.8	48.0	44.9	46.4
Wo	49.1	50.5	48.4	48.7	51.1	49.1
M2	0.968	1.007	0.994	1.000	1.003	>0.910[a]

[a]The actual site occupancy by the M2-preferring cations is likely higher (because Na abundance was not determined) but probably still less than 1.000.

n.d. = not determined.

M2 = atomic abundance of M2 site-preferring cations; i.e., mol% (Na + Co + Cr + Mn + Zn + Ca). A full M2 site that would exclude Fe^{2+} would have a value of 1.000.

factor of ten (Cloutis 1985; Straub et al. 1991). Table 1 provides compositional information for a number of paired type A and B clinopyroxenes; their spectra are shown in Fig. 2. As can be seen from these data, small differences in composition can lead to drastic variations in the appearance of Fe^{2+}-associated absorption bands in the 1 and 2 µm regions.

The terrestrial spectral type A clinopyroxenes whose spectra best match the spectrum of Božněmcová are all Fe^{3+}-free samples: PYX009, PYX020, and PYX150 (Fig. 2). These spectra can be compared to the spectrum of Božněmcová (Fig. 3), where all the spectra have been normalized to 1 at 0.55 µm. All three spectral type A pyroxenes (PYX009, PYX020, and PYX150) contain enough M2-partitioned cations (Ca, Na, Co, Zn, Cr, Mn) to fully occupy the M2 site, and thereby exclude Fe^{2+} from this site. The absence of Fe^{3+} in these three samples is useful for comparative purposes because the clinopyroxene in angrites is Fe^{3+}-free (Mittlefehldt et al. 1998). The presence of Fe^{3+} results in a more red-sloped spectrum as well as an Fe^{3+}-Fe^{2+} charge transfer band in the 0.75 µm region (Cloutis 2002; Schade et al. 2004), complicating spectral comparisons.

These three spectral type A clinopyroxenes exhibit a number of spectral features consistent with Božněmcová. These include: two absorption bands near 0.95 and 1.15 µm (all three sample spectra); roughly similar band width (full width at half maximum; FWHM) and overall shape in the 1 µm region (PYX009); a reflectance maximum near 0.75 µm

(PYX009 and PYX020); and a spectral slope similar to Božněmcová in the 0.35–0.65 µm region (PYX009). The differences between the three type A clinopyroxene spectra can largely be attributed to differences in Fe^{2+} content (all three are pure clinopyroxene on the basis of X-ray diffraction analysis). PYX009 is the most Fe^{2+}-rich ($Fs_{9.7}$) and has the deepest absorption bands in the 1 µm region.

Further compositional constraints on the surface mineralogy of Božněmcová can be derived from some of the remaining differences between the asteroid and spectral type A clinopyroxene spectra. The overall shape of the major absorption band in the 1 µm region of Božněmcová (with slightly stronger absorption near 0.95 versus 1.15 µm) is most similar to intermediate spectral type clinopyroxenes, specifically those that show a barely discernible absorption feature in the 2.2 µm region (e.g., CPX13 in Schade et al. 2004). Unfortunately, the compositional data for this sample are not complete enough to determine, from stoichiometry, whether any Fe^{2+} resides in the M2 site. A clinopyroxene of similar overall Fe^{2+} content to PYX020 (PYX018), but which contains ~10% of its Fe^{2+} in the M2 site, exhibits type B spectral behavior, with no strong evidence for the M1 absorption bands (Fig. 2). Thus Fe^{2+} in the Božněmcová clinopyroxene is probably strongly partitioned into the M1 site, but perhaps not exclusively so, on the order of 90–100%.

The major spectral mismatches between the type A clinopyroxene spectra and Božněmcová are: 1) reflectance near 0.95 µm is higher than near 1.15 µm in Božněmcová,
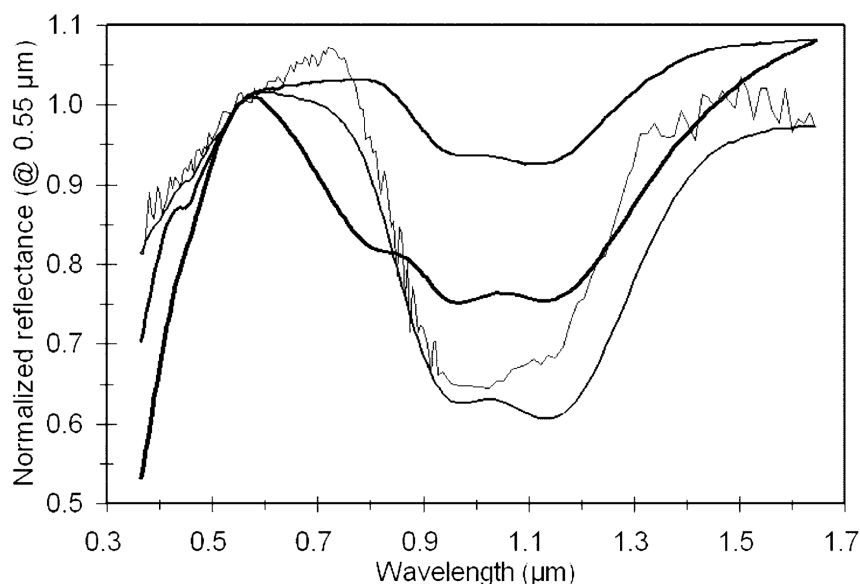
Fig. 3. Reflectance spectra of Božněmcová (thinnest line; 0.3–2.6 μm normalized to 1 at 0.55 μm), and three type A clinopyroxene spectra (all 45–90 μm grain size; measured at HOSERLab and listed in order of increasing line thickness on the plot): PYX009, PYX020, and PYX150. See Table 1 for clinopyroxene compositions. The laboratory spectra have been resampled to the Božněmcová band passes.

opposite to the relationship for the type A clinopyroxenes; and 2) FWHM of the 1 μm absorption feature is less in Božněmcová than in the type A clinopyroxene spectra used in this study. The difference in relative depths of the 0.95 and 1.15 μm absorption features may be due to a contribution from crystal field transitions of a small amount of Fe^{2+} (<10% of total Fe^{2+}) located in the M2 crystallographic site, or to an additional phase.

Plausible Candidate Meteorites: Angrites

Mineralogy

Given that spectral type A clinopyroxene (specifically PYX009) provides a good overall match to Božněmcová, we can look at what meteorite classes contain significant amounts of this type of clinopyroxene, as well as what other minerals are present in these classes, how they may modify the spectra of type A clinopyroxenes, and whether these modifications can reconcile some of the spectral differences between type A clinopyroxene spectra and Božněmcová. As discussed above, to first order, the spectrum of Božněmcová is consistent with a spectral type A Fe^{3+}-free clinopyroxene-dominated assemblage.

Clinopyroxene with a composition that would give rise to spectral type A behavior is not a common phase in meteorites. The only known meteorite group that contains this phase in abundance is the angrites (Mittlefehldt et al. 2002). To date, nine angrite meteorites have been identified: Angra dos Reis (Prinz et al. 1977), Asuka-881371 (Yanai 1991), D'Orbigny (Grossman and Zipfel 2001), Lewis Cliff (LEW) 86010 (McKay et al. 1988), LEW 87051 (McKay et al. 1990), an

unnamed sample from Morocco (Jambon et al. 2002; provisionally Northwest Africa [NWA] 1296), NWA 1299 (Kuehner et al. 2006), NWA 1670 (Mikouchi et al. 2003), and Sahara 99555 (Mikouchi et al. 2000). The mineralogical and compositional properties of these angrites relevant to properties inferred for Božněmcová are provided in Tables 2 and 3.

This information can be used to infer expected spectral behavior, and in some cases to compare the expected and measured spectral properties. It should be noted that assigning angrites to a spectral group (type A, B, or intermediate) requires a knowledge of the abundance of all the cations that show M1 or M2 site preferences (Cloutis 2002). Such data is not available for all of the angrites. In addition, the clinopyroxene in most angrites shows compositional zonations; the use of an average composition may therefore not accurately reflect the spectral complexity that angrites may exhibit. Finally, the difference in the M1:M2 Fe^{2+} ratio required to shift a clinopyroxene spectrum between type A, intermediate, and type B can be small, on the order of a few tenths of a wt% FeO (Table 2; Fig. 2), since the amount of Fe^{2+} required to produce an absorption band of comparable strength is much higher for M1 than M2 (Straub et al. 1991; Schade et al. 2004).

From the available compositional information, three spectral groups are expected for the clinopyroxenes in angrites: Angra dos Reis, Asuka-881371, and NWA 1670 are expected to exhibit spectral type B behavior; D'Orbigny, LEW 87051, NWA 1296, and Sahara 99555 are expected to exhibit intermediate type A and B spectral behavior; and LEW 86010 and NWA 1299 are expected to exhibit type A-

Table 2. Relevant mineralogies and compositions of angrites and those inferred for Božněmcová.

Meteorite	Wt% mineral phases			CPX FeO content (average; wt%)[a]	CPX spectral type present or expected	Source of data
	CPX	PLG	OLV			
ADOR	93	0	5.5	6.7	B	a, b, c
Asuka-881371	5.5	27.4	55.3	14.8	B	d e, f
Asuka-881371	20	36	44		B	g
D'Orbigny	27.7	39.4	31.3	16.3	A–B	h, i, j
LEW 86010	60	20	20	10.3	A[b]	k
LEW 86010	43.3	31.8	23.5			l
LEW 86010	58.3	20.3	21.0			m
LEW 86010	20.9	37.2	39.2			n
LEW 87051	20.5	34.1	44.7	18.5	A–B	o, p
LEW 87051	16.5	25.1	54.8			n
LEW 87051[c]	45.5	41.7	12.8			o, q
NWA 1296	34	32	31	n.a.	A–B	r, s
NWA1299	23	1	64	10	B	
NWA 1670	24	23	52	14.4	B	u, v
Sahara 99555	24	33	42	18	A–B	w, x
Božněmcová	55–75	33	0–20	6–11	A	

[a]Wt% FeO content is used rather than Fs content because only partial pyroxene analyses are available for many angrites.
[b]LEW 86010 clinopyroxene composition is dominated by Fe^{2+}-free M2 site occupancies, although some individual analyses are consistent with some Fe^{2+} M2 site occupancy (Crozaz and McKay 1990).
[c]CIPW normative composition for the glass phase, which accounts for 75% of this meteorite by volume.
Abbreviations: CPX = clinopyroxene; PLG = plagioclase feldspar; OLV = olivine plus kirschteinite; n.a. = data not available.
Sources of data: a = Gomes and Keil (1980). b = Ma et al. (1977). c = Prinz et al. (1977). d = Mittlefehldt et al. (1998). e = Yanai (1991). f = McKay (unpublished data). g = Yanai (unpublished data). h = Grossman and Zipfel (2001). i = Mikouchi and McKay (2001). j = Kurat et al. (2004). k = Goodrich (1988). l = McKay et al. (1988). m = Prinz et al. (1988). n = Mittlefehldt and Lindstrom (1990). o = McKay et al. (1990). p = Yanai and Noda (2004). q = Prinz et al. (1990). r = Jambon et al. (2002). s = Jambon (unpublished data). t = Kuehner et al. (2006). u = Mikouchi et al. (2003). v = Mikouchi (unpublished data). w = Mikouchi et al. (2000). x = Burbine et al. (2001).

Table 3. Pyroxene Fe^{2+} site occupancies (those for Božněmcová are predicted as described in the text).

	Average Fe^{2+} in M2 site (mol%)	Average Fe^{2+} in M1 site (mol%)	Fe^{2+} ratio: M2/M1	Source of data
Type A clinopyroxenes				
PYX009	0.000	0.191	0.00	a
PYX020	0.000	0.062	0.00	a
PYX150	0.000	0.077	0.00	a
Angrites				
ADOR	0.025	0.185	0.13	b
Asuka 881371	0.027	0.459	0.06	c
D'Orbigny	0.044	0.482	0.09	d
LEW 86010[a]	0.000	0.328	0.00	e
LEW 87051	<0.060	<0.20	<0.30	f
NWA 1296	0.058	0.464	0.12	g
NWA 1299	0.000	~0.2	0.00	h
NWA 1670	0.072	0.394	0.18	i
Sahara 99555	n.a.	n.a.		j
Božněmcová	0.010–0.018	0.2–0.35	0.05	a

[a]LEW 86010 clinopyroxene composition is dominated by Fe^{2+}-free M2 site occupancies, although some individual analyses are consistent with some Fe^{2+} site occupancy.
Abbreviations: n.a. = data not available.
Sources of data: a = this study. b = Gomes and Keil (1980). c = Mikouchi et al. (1996) and McKay (unpublished data). d = Kurat et al. (2004). e = McKay et al. (1988). f = McKay et al. (1990). g = Jambon et al. (2005). h = Kuehner et al. (2006). i = Mikouchi (unpublished data). j = Mikouchi et al. (2000).

dominated spectral behavior. In the case of LEW 86010, the majority of the clinopyroxene spot analyses suggest that we would expect spectral type A behavior, but a number of individual spot analyses are consistent with an expectation of spectral type B behavior (McKay et al. 1988). It should be noted that the compositions of the available angrite pyroxenes are generally very close to the point at which type A spectral behavior is expected, and there is commonly some heterogeneity in angritic clinopyroxene compositions. The inferred spectral behavior for at least three angrites, Angra dos Reis, D'Orbigny, and Sahara 99555 are supported by Mössbauer analysis of Fe^{2+} site occupancies (Hoffman 2002).

The clinopyroxene in angrites is Al- and Ti-rich; this type of pyroxene is commonly termed fassaite. Fassaites commonly exhibit a weak absorption band near 0.46 μm, attributable to Ti^{3+} crystal field transitions, when Ti abundances and reflectance in this region are high enough to enable detection of this band (Cloutis 2002). Terrestrial Al- and Ti-rich clinopyroxenes are generally much redder (reflectance increasing toward longer wavelengths) than Božněmcová. This is attributable to the presence of Fe^{3+}, which can result in an intense Fe^{2+}-Fe^{3+} charge transfer absorption band in the 0.75 μm region; this reduces reflectance across a wide range, resulting in a red-sloped spectrum. In the case of Angra dos Reis, its strong red slope is attributable to an intense charge transfer band located near 0.48 μm, involving some combination(s) of Ti^{3+}, Ti^{4+}, Fe^{2+}, and O^{2-} (Mao et al. 1977). Other angrites (D'Orbigny, Sahara 99555, LEW 86010) do not show as intense a red slope (Burbine et al. 2006), suggesting that such the appearance of charge transfers is dependent on both cation type and cation site occupancies.

The spectrum of Božněmcová does not show evidence for a band in the 0.46–048 μm region (Fig. 1), or for the presence of the 0.75 μm Fe^{2+}-Fe^{3+} charge transfer absorption feature. The latter is strong evidence for an Fe^{3+}-free (or nearly so) clinopyroxene on Božněmcová, consistent with the composition of angritic clinopyroxene (Hazen and Finger 1977; Ma et al. 1977). The former suggests that Božněmcová differs from Angra dos Reis in terms of abundances and/or site occupancies of transition series elements.

Other Minerals in Angrites

The spectral mismatches between Božněmcová and the available type A clinopyroxene spectra suggests that either we have not identified a spectrally suitable type A clinopyroxene or that at least one additional phase is likely present on Božněmcová. Using the inferred gross mineralogical similarities between Božněmcová and angrites, we can examine the spectrum-altering properties of the additional phases present in angrites. The spectral differences between Božněmcová and spectral type A clinopyroxene suggest that these additional phases are spectrally quite neutral, or otherwise additional absorption features would be present. If these accessory minerals are spectrally featured,

Table 4. Wt% abundances of end members used for intimate mixtures.

Sample	Pyroxene (PYX009)	Plagioclase feldspar (PLG108)	Olivine (OLV003)
BOZ001	91	9	0
BOZ002	83	17	0
BOZ003	77	15	8
BOZ004	72	14	14
BOZ005	67	13	20
BOZ006	62.5	12.5	12.5
BOZ007	59	12	29
BOZ008	45.5	9	45.5
BOZ009	33.3	33.3	33.3

they must be present in amounts that are spectrally insignificant.

The major accessory phases present in angrites are olivine and plagioclase feldspar. Most angrites contain olivine and plagioclase feldspars at a level of up to a few tens of a percent (Table 2). The effects that these two phases have on clinopyroxene spectra are considered in detail, as they may explain the remaining spectral mismatches between Božněmcová and spectral type A clinopyroxenes. We have measured the reflectance spectra of a number of olivines and plagioclase feldspars, as well as intimate mixtures involving 45–90 μm size fractions of a type A clinopyroxene PYX009, a plagioclase feldspar (PLG108, An_{85}), and an olivine (OLV003, Fa_{10}) (Table 4).

Angrites contain variable amounts of plagioclase feldspar, up to 42 wt% (Table 2). Plagioclase feldspar is spectrally quite neutral in the 0.35–1.7 μm region, largely due to its low abundance of transition series elements (Adams and Goullaud 1978). It sometimes exhibits a broad and weak absorption band in the 1.3 μm region, whose strength is correlated with iron content (Adams and Goullaud 1978). The spectrum-altering effects of plagioclase feldspar were examined by measuring reflectance spectra of intimate mixtures of type A clinopyroxene (PYX009) and an anorthitic plagioclase feldspar (PLG108, An 85). The plagioclase in angrites is very anorthitic (e.g., McKay et al. 1988, 1990; Jambon et al. 2005). The plagioclase feldspar used in the mixtures has a weak band centered near 1.3 μm. The reflectance spectra of these mixtures indicates that, at least for moderate abundances of plagioclase feldspar (up to a 1:5 plagioclase feldspar:clinopyroxene ratio), the plagioclase feldspar has little effect on the spectra with the exception of a modest increase in overall reflectance and a slight decrease in absorption band depths in the 1 μm region (Fig. 4). This is similar to the results found by other investigators for plagioclase feldspar + orthopyroxene mixtures (Nash and Conel 1974). Plagioclase feldspar would likely have to be present at a plagioclase feldspar:clinopyroxene ratio of at least 1:1 to have a significant impact on absorption band depths and widths (Nash and Conel 1974). Plagioclase feldspar:clinopyroxene ratios in angrites range from ~0 to as high as 5:1 (Table 2).
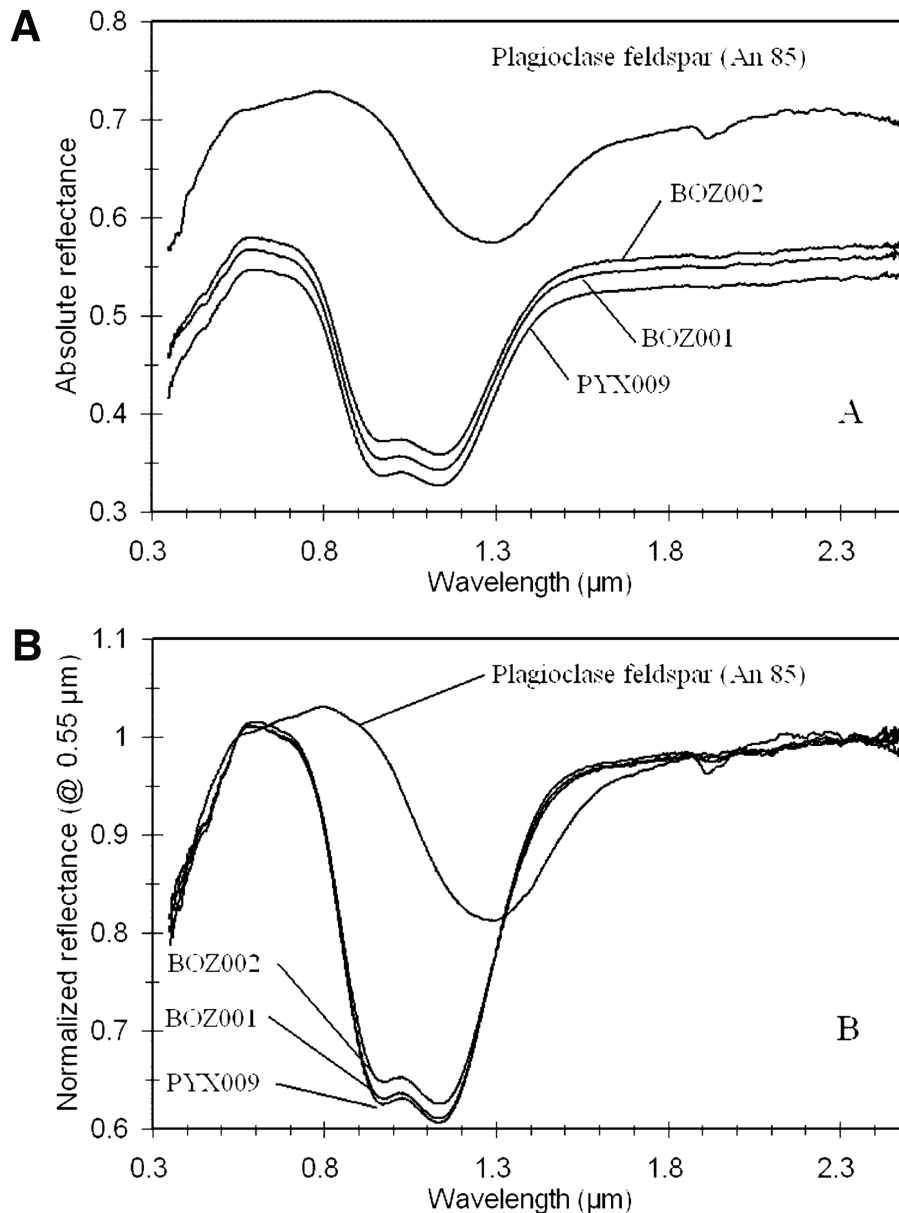
Fig. 4. Absolute (a) and normalized (b) HOSERLab reflectance spectra of PYX009, PLG108, and mineral mixtures BOZ001 and 002 (see Table 4 for description of mixtures). Reflectance in the 1 μm region in both the absolute and normalized spectra increases with increasing plagioclase feldspar content.

Comparing two three-component mixtures that differ only in terms of plagioclase feldspar abundance better illustrates the changes inherent in increasing plagioclase feldspar abundance (Fig. 5). Increasing plagioclase feldspar abundance from 9 to 33% results in a 15% decrease in band depth and 10% decrease in FWHM. Thus, a type A Fe^{3+}-free clinopyroxene (with a composition similar to that of the bulk of the angrites) mixed with a few tens of percent of plagioclase feldspar could reconcile many of the disparities between Božněmcová and type A clinopyroxene.

The other major phase in angrites is olivine, specifically forsterite-fayalite (Fe-Mg olivine) and kirschsteinite-monticellite (Ca-Fe-Mg olivine). Ca-Fe-Mg olivine can be present in approximately equal amounts with Ca-poor Fe-Mg olivine, and Ca and Mg contents are roughly inversely correlated (Mikouchi et al. 2000; Mikouchi and McKay 2001; Mittlefehldt et al. 2002). Solid solution exists between kirschsteinite ($CaFeSiO_4$) and monticellite ($CaMgSiO_4$) (Brown 1982). Fe-Mg olivine + Ca-Fe-Mg olivine abundances can exceed clinopyroxene content in some angrites (Table 2). A series of three component intimate mixtures (clinopyroxene + plagioclase feldspar + Fe-Mg olivine) were spectrally characterized to determine how olivine affects type A clinopyroxene spectra and, if olivine is
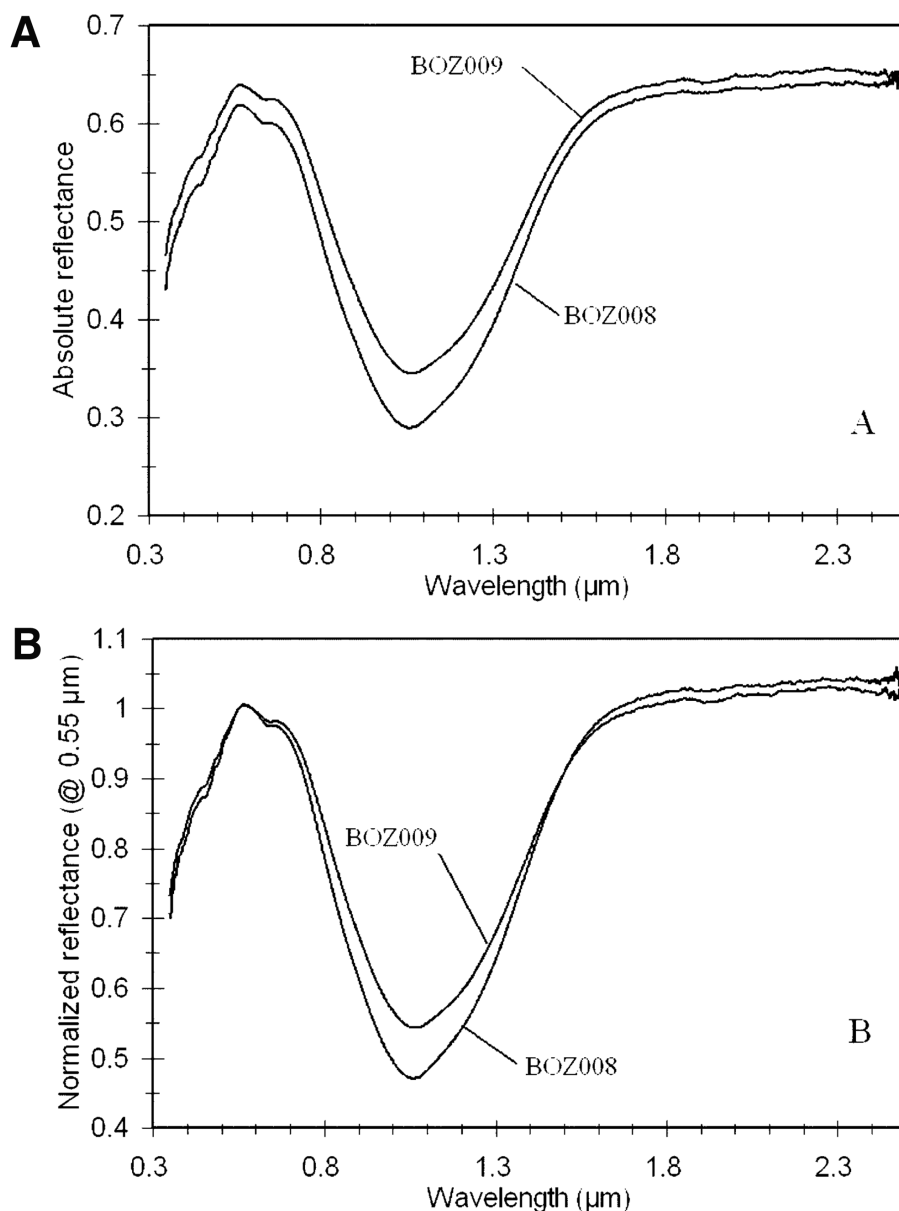
Fig. 5. Absolute (a) and normalized (b) HOSERLab reflectance spectra of mineral mixtures BOZ008 and BOZ009 (see Table 4 for description of mixtures).

present on Božněmcová, whether its abundance can be constrained. A series of mixtures with progressively increasing olivine content are shown in Fig. 6. It can be seen that by the time the olivine:clinopyroxene ratio reaches ~1:4, olivine begins to dominate the spectrum in the 1 μm region: the distinctive two-band structure of type A clinopyroxene in the 1 μm region is lost, replaced by a single band near 1.05 μm, characteristic of Fe-Mg olivine. Increasing olivine content also results in a progressive broadening of the 1 μm region absorption feature.

Figure 7 shows the reflectance spectrum of monticellite, the magnesium-rich variety of kirschsteinite (our sample contains 3 mol% Fe^{2+}). Its spectrum shows evidence for some incipient alteration (absorption bands near 1.4 and 1.9 μm). Its band center is located near 0.947 μm, well below the range for forsterite-fayalite (King and Ridley 1987). This band is attributed to crystal field transitions in Fe^{2+} and suggests that the Ca-Fe-Mg olivine series has an absorption band in the same region as the shorter wavelength M1 Fe^{2+} band in type A clinopyroxene. The presence of Ca-Fe-Mg olivine would increase the depth of the 0.95 μm absorption feature relative to the 1.15 μm feature, and therefore could account for the band depth difference in Božněmcová relative to the spectral type A clinopyroxenes. Thus, two alternative explanations exist for the appearance of the 1 μm region feature: a contribution from a clinopyroxene M2 Fe^{2+} charge transfer
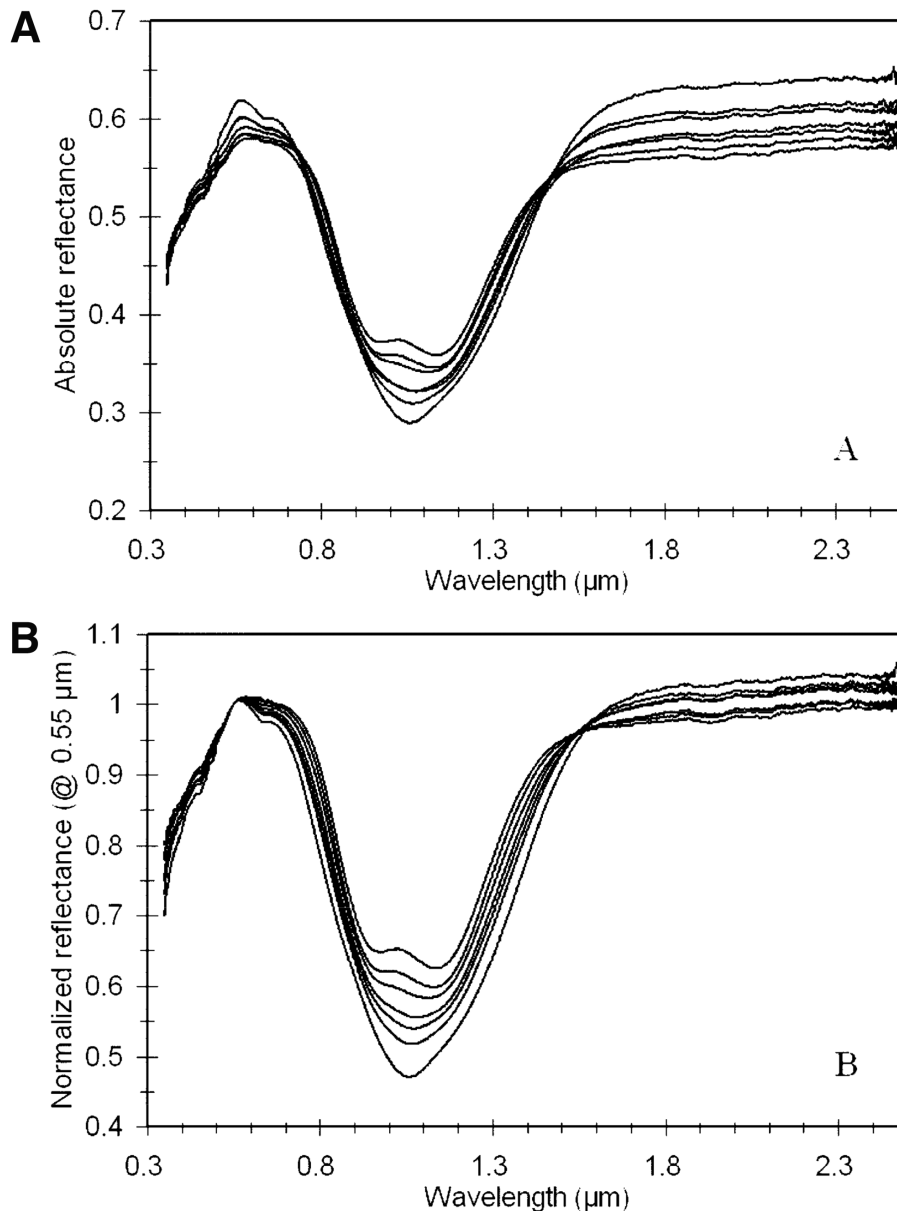
Fig. 6. Absolute (a) and normalized (b) HOSERLab reflectance spectra of mixtures BOZ002–008. This series shows the effects of increasing olivine content on type A clinopyroxene + plagioclase feldspar mixtures (this ratio is constant at 5:1). Increasing olivine content correlates with decreasing reflectance in the 1 μm region and increasing reflectance at 1.7 μm in both figures. Increasing olivine content correlates with increasing reflectance at 0.55 μm in (a), and decreasing reflectance at 0.55 μm in (b).

absorption, or from a Ca-Fe-Mg olivine. The former would be accompanied by an additional band near 2.2 μm, while the latter would not.

Angrite Pyroxene Composition

One additional factor that needs to be considered in the comparison of Božněmcová to the angrites is the composition of angritic pyroxene. With the exception of Angra dos Reis, angritic pyroxene is more Fe^{2+}-rich (10–18% FeO) than the most Fe^{2+}-rich type A clinopyroxene used in this study

(PYX009, 6.2% FeO). While more Fe^{2+}-rich type A clinopyroxenes were available, all contained enough Fe^{3+} to result in an intense Fe^{2+}-Fe^{3+} charge transfer band near 0.75 μm, and an overall red-sloped spectrum, making spectral comparisons with Božněmcová unreliable, as the location of the continuum for band isolation could not be confidently assigned. The pervasive nature of this feature can be inferred from the data for PYX150; it shows an absorption feature near 0.75 μm, but no Fe^{3+} was detected during compositional analysis (~0.01 wt% Fe_2O_3 detection limit).

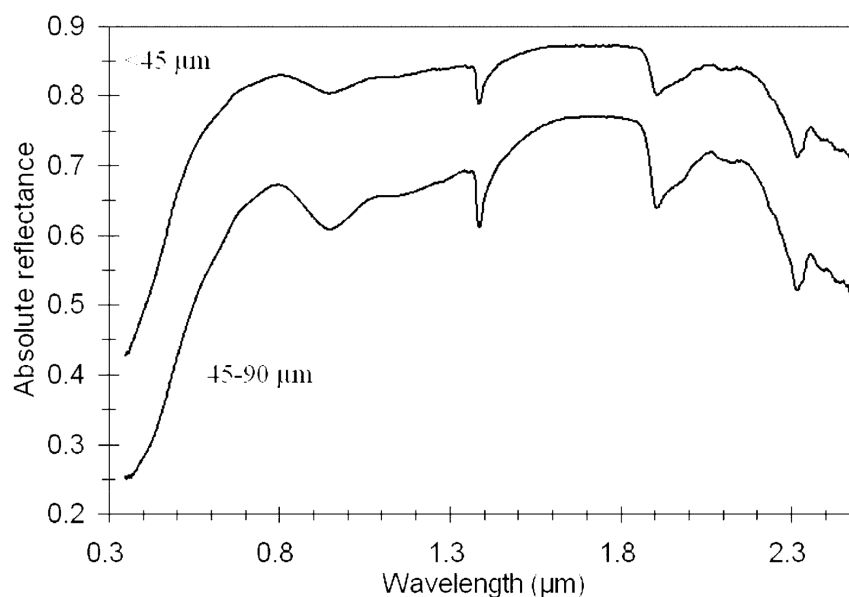From the available clinopyroxene spectral database it is

Fig. 7. HOSERLab reflectance spectra of two grain sizes of monticellite—a Ca-Fe-Mg olivine. Absorption bands in the 1.4, 1.9, and 2.3 μm region are associated with incipient alteration.

known that the depth of the absorption bands in the 1 μm region increases with increasing FeO content for a given grain size. Thus, while PYX009 has the same approximate band depth as Božněmcová in the 1 μm region, this effect can also be mimicked by a more Fe^{2+}-rich type A clinopyroxene of a smaller grain size. To determine what effect reducing grain size and increasing Fe^{2+} content have, we examined the available type A clinopyroxene spectra and found that decreasing grain size (at least for the <45 versus 45–90 μm sizes) has no major effect (<6% variation) on band FWHM. Increasing Fe^{2+} content, however, does lead to an increase in FWHM for a given grain size (~20% increase when Fs content increases from 3 to 10). The FWHM and band depth of the 1 μm feature in the Božněmcová spectrum cannot be simultaneously matched solely by any type A clinopyroxene. Increasing Fe^{2+} content would improve the match to band depth but would result in an increase in FWHM. Decreasing the grain size at the same time would reduce band depth but would not appreciably affect FWHM. Consequently, an additional phase seems necessary to improve the spectral match between type A clinopyroxene and Božněmcová, and, as discussed above, plagioclase feldspar is the best candidate, both mineralogically and spectrally.

ANGRITE SPECTRA AND BOŽNĚMCOVÁ

Of the ten angrites, four have been spectrally characterized to date: Angra dos Reis, D'Orbigny, Sahara 99555, and LEW 86010 (Gaffey 1976; Burbine et al. 2001; Burbine et al. 2006; this study). All four exhibit spectral behavior consistent with their mineralogies and compositions (Tables 2 and 3; Fig. 8). Angra dos Reis is of spectral type B

and radically different from Božněmcová (Gaffey 1976), while the other three exhibit spectral characteristics consistent with type A and/or A-dominated with a small contribution from type B. The spectra of these three angrites exhibit weaker than expected absorption bands in the 2 μm region than would be the case for pure spectral type B behavior, as well as significant spectral modifications in the 1 μm region due to abundant olivine. The angrite spectra all have redder slopes in the 0.35–0.75 μm interval than Božněmcová (Fig. 8). The cause of the greater red slope in the angrite spectra versus Božněmcová is not known, but may be attributable to terrestrial weathering (Salisbury et al. 1975), the presence of fusion crust, other accessory phases, or differences in transition series element abundances and site occupancies leading to intervalence charge transfers.

Overall, the angrite spectra (discussed in greater detail in Burbine et al. 2006) exhibit features consistent with both the foregoing interpretations of type A clinopyroxene + olivine, as well their mineralogies. The 1 μm region of the spectra of Sahara 99555, D'Orbigny, and LEW 86010 are all strongly affected by the olivine, which results in a change of the absorption feature in the 1 μm region from the distinct two-band structure of type A clinopyroxene to one more dominated by olivine (Fig. 6). Therefore the clinopyroxene: olivine ratio on Božněmcová should be higher than that of these three angrites. Their ratios range from 0.5 to 3, all less than the lower limit of 4 for Božněmcová derived from the mineral mixture spectra. The LEW 86010 spectrum is closest to that of Božněmcová in terms of exhibiting some evidence for a two-band structure in the 1 μm region, as well as having its composite band minimum at the shortest wavelength (~1.04 μm). This is consistent with the fact that it also has a
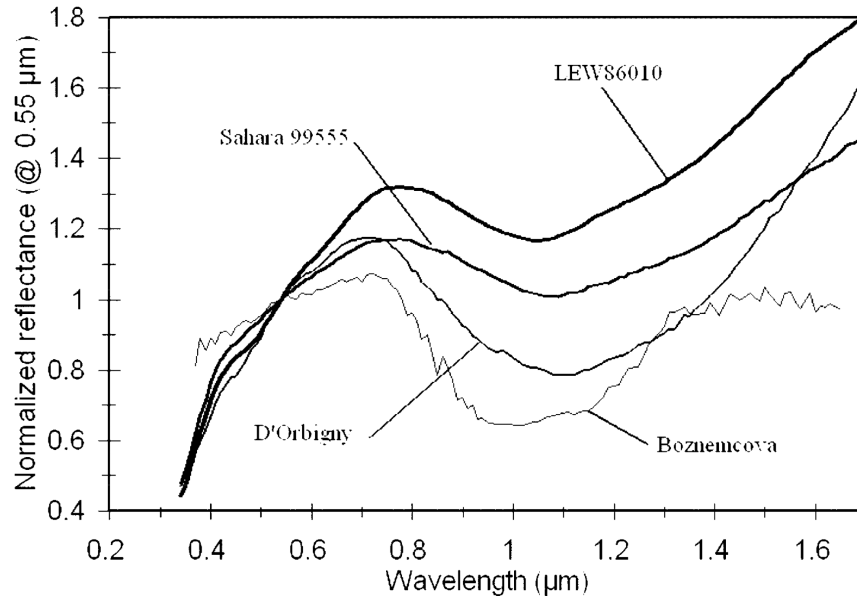
Fig. 8. Normalized reflectance spectra (0.35 to 1.65 μm). From thinnest to thickest line: Božněmcová, D'Orbigny, Sahara 99555, and LEW 86010. The angrite spectra were measured at RELAB and have been resampled to the Božněmcová band passes.

higher clinopyroxene:olivine ratio than D'Orbigny and Sahara 99555.

At longer wavelengths (beyond 1.7 μm) there is little likelihood that additional spectrally diagnostic information would be derived. The available angrite spectra that exhibit spectral type A behavior in the 1 μm region (D'Orbigny, Sahara 99555, and LEW 86010) do not exhibit well-resolved absorption bands in the 2–2.5 μm region, but rather are characterized by a change in spectral slope near 2 μm (Burbine et al. 2006). This is likely due to the influence of a very weak M2 Fe^{2+} crystal field transition; as was mentioned, the pyroxene in most angrites is compositionally heterogeneous, and hence some small proportion of the clinopyroxene may contain some Fe^{2+} in the M2 site. The other major minerals in angrites, Fe-Mg and Ca-Fe-Mg olivine and plagioclase feldspar do not exhibit diagnostic absorption bands in this region.

INFERRED SURFACE COMPOSITION
OF BOŽNĚMCOVÁ

We can compare the spectrum of Božněmcová to our type A clinopyroxenes, along with the data on the spectrum-altering effects of plagioclase feldspar and olivine, as well as the angrite spectra, to derive a spectrally and petrologically consistent assemblage for this asteroid. A pure spectral type A or type A-dominated clinopyroxene is present on Božněmcová and accounts for the distinct absorption features in the 1 μm region. A few tens of a percent of plagioclase feldspar is also present on Božněmcová. This is required to reconcile the difference in the width of the 1 μm region

absorption feature in Božněmcová versus the type A clinopyroxenes. The clinopyroxene on Božněmcová is also more Fe^{2+}-rich than PYX009 (Fs 10). This higher Fe^{2+} content would lead to deeper absorption bands in the 1 μm region, and the presence of plagioclase feldspar would simultaneously reduce its depth and width, bringing it closer in line with Božněmcová's spectrum.

Laboratory spectra of orthopyroxene + plagioclase feldspar mixtures (Nash and Conel 1974) and the current mineral mixtures suggest that a pyroxene:plagioclase feldspar ratio of ~2–3 is required to reduce the widths of absorption bands in the 1 μm region by an appropriate magnitude. The required clinopyroxene Fe^{2+} content is coupled to the plagioclase feldspar abundance, and given the constraints placed on the latter, the clinopyroxene composition is constrained to $Fs_{\sim10-20}$. The laboratory mixture data suggest that the clinopyroxene:olivine ratio for Božněmcová must be >~3, otherwise the shape of the 1 μm region absorption feature would be excessively modified. Of the known angrites, only Angra dos Reis and, possibly, LEW 86010 satisfy this constraint (Table 2).

Overall, the inferred surficial mineralogy of Božněmcová consists of a spectral type A clinopyroxene-dominated surface ($Fs_{\sim10-20}$) with a clinopyroxene: plagioclase feldspar ratio of between ~2 and 3, a clinopyroxene:olivine ratio of >~3. This translates into ~55–75 wt% clinopyroxene, ~20–33 wt% plagioclase feldspar, and 0–20 wt% olivine.

Mineralogically, this inferred surface assemblage is similar to two analysis of the angrite LEW 86010 (Goodrich 1988; Prinz et al. 1988) (Table 2). However two other

analyses of LEW 86010 (McKay et al. 1988; Mittlefehldt and Lindstrom 1990) (Table 2) indicate a lower clinopyroxene: olivine ratio. It appears likely that LEW 86010 is heterogeneous on the mm–cm scale. Božněmcová's spectrum is consistent with the former determinations. None of the other angrites for which adequate compositional and mineralogical information is available are fully consistent with the values derived for Božněmcová. The major discrepancies between the inferred surface composition of Božněmcová and the angrites relate to the clinopyroxene: olivine ratio, with the angrites generally containing too much olivine (Table 2). However, this interpretation is complicated by the fact that the relative abundances of Ca-poor and Ca-rich olivines are not well determined for many of the angrites.

ORIGIN OF BOŽNĚMCOVÁ

Given the inferred mineralogy and composition of Božněmcová and gross similarities to angrites, what can we infer about the origin of this asteroid? It is widely accepted that angrites are crustal igneous rocks formed by a combination of partial melting, melt migration, olivine fractionation, and fractional crystallization (Mittlefehldt et al. 1998), although other types of origins have been proposed for some angrites (Kurat et al. 2004; Varela et al. 2005). They appear to have formed on a separate parent body from other differentiated meteorites, although angrite-like clasts are known from ureilites (Mittlefehldt et al. 1998).

Among the angrites, the petrogenesis of LEW 86010 is perhaps the best understood (Mittlefehldt et al. 1998, 2002). Partial melting experiments of the Allende CV3 chondrite under oxidizing conditions (IW+1) (Jurewicz et al. 1993), melting experiments on a LEW 86010 composition (McKay et al. 1994), and trace element data for LEW 86010 minerals (Crozaz and McKay 1990) all suggest formation by low degrees (~20%) of partial melting of a carbonaceous chondrite precursor followed by closed system crystallization. There are difficulties in relating known angrites to one another via partial melting, fractional crystallization, or olivine control (the addition or subtraction of olivine) (Mittlefehldt et al. 2002). Thus, it appears that the petrogenesis of the angrite parent body as a whole is reasonably complicated and still poorly understood. The results of Jurewicz et al. (1993) suggest that formation of a high-Ca pyroxene, low-olivine content, moderate plagioclase feldspar content surface (as inferred for Božněmcová) is possible through fractional crystallization of olivine from a 1200° Allende angritic melt. Crystallization and removal of the olivine would result in an increase in the CaO content of the liquid, which would then likely stabilize CaO-bearing phases such as anorthitic plagioclase and calcic pyroxene.

Božněmcová appears to have experienced significant degrees of partial melting and differentiation under oxidizing conditions with the formation of an angrite-like crust. Two plausible explanations are most likely to explain the current status of Božněmcová. One is that it has been largely unaffected by collisions and we are seeing an essentially intact crust. Disruption or deep impacts should have excavated and revealed olivine-rich mantle. There is no spectral evidence for abundant olivine, and to date no genetic links have been made between angrites and any olivine-rich meteorites. The second explanation for Božněmcová is that it is a disrupted fragment of a larger body which only sampled the near-surface angritic melts, akin to the eucrite-like vestoids (Binzel and Xu 1993). Resolution of this conundrum will probably require determination of Božněmcová's size, increased or improved spectral coverage, and perhaps rotational coverage, as well as the identification of other angrite-like asteroids.

SUMMARY

The inferred surface composition of Božněmcová consists of an assemblage dominated by clinopyroxene and plagioclase feldspar. The clinopyroxene has a high abundance of cations that partition strongly into the M2 crystallographic site (some combination of Ca, Na, Co, Zn, Cr, Mn), and with an Fs content of ~10–20. The high abundance of these M2-partitioned cations is necessary to account for the spectral type A behavior of the abundant clinopyroxene. The uncertainty in pyroxene Fs content is related, in part, to the lack of systematic relationships between Fs content and absorption band wavelength positions. Abundant plagioclase feldspar also seems necessary to fully reconcile type A clinopyroxene spectra with the spectrum of Božněmcová. The spectrum-altering effects of changes in plagioclase abundance, pyroxene Fs content, and grain size are coupled. The clinopyroxene:plagioclase feldspar ratio is between ~2 and 3 (~55–75% clinopyroxene, ~20–33% plagioclase feldspar). If olivine is present, the clinopyroxene:olivine ratio is >~3 (<20% olivine). The derived mineralogy of Božněmcová is broadly similar to angrite meteorites. The data suggest that Božněmcová formed by melting and differentiation of an oxidized chondritic precursor and probably represents an unsampled angrite-like body.

Editorial Handling—Dr. Carlé Pieters

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