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APPENDIX B. EXPLANATION OF AGE INTERPRETATIONS OF SPECIFIC CORRELATED TEPHRAS IN THE SANTA FE GROUP

A number of tephra beds were used as age datums in our study. Many, such as the No. 2 and No. 4 white ashes in the Skull Ridge Member of the Tesuque Formation, have direct radiometric ages. Others, such as the upper green coarse white ash, have interpolated ages from radiometrically dated tephras or lavas. This appendix provides support for the specific age values we chose for these important tephra.

Radiometric ages come from two laboratories: 1) the USGS laboratory in Menlo Park, California, and 2) the New Mexico Geochronology Research Laboratory at New Mexico Tech, Socorro, New Mexico. The USGS laboratory conducted $^{40}Ar/^{39}Ar$ analyses of an ash they identified as "Nambé white ash," Skull Ridge Member ashes No. 2, 3, and 4, and a "thin white ash" (TW) in the Pojoaque white ash zone (Izett and Obradovich, 2001). The New Mexico Geochronology Research Laboratory performed $^{40}Ar/^{39}Ar$ dating of the Skull Ridge No. 4 white ash (McIntosh and Quade, 1995), the lower coarse white ash zone (Appendix C), and the lower and upper Chamita tuffaceous zones (McIntosh and Quade, 1995). It should be noted that the New Mexico Geochronology Research Laboratory used the Fish Canyon Tuff sanidine (27.84 Ma relative to MMhb-1 hornblende at 520.4 Ma; Samson and Alexander, 1987) as a standard whereas the analyses from the USGS laboratory used Taylor Creek Rhyolite as a standard. The age of the latter standard is based on an internally consistent set of laboratory standard values measured in the USGS Menlo Park laboratory, and results in a measured age that is 1.26% younger (Izett and Obradovich, 2001) than the internationally adopted mean value of 520.4 Ma for the MMhb-1 hornblende (Samson and Alexander, 1987). According to Izett and Obradovich

(2001), their ages can be normalized approximately to an age of 520.4 Ma for the Mmhb-1 hornblende by multiplying their ages by a factor of 1.0144. To be consistent with samples of the New Mexico Geochronology Research laboratory, we used this factor to convert the ages of the samples in Izett and Obradovich (2001).

Below, we provide brief arguments and discussion regarding the ages we chose for tephra marker beds.

Nambé white ashes

Galusha and Blick (1971) and Barghoorn (1981 and 1985) recognize a laterally extensive, relatively thick (20-70 cm), white ash bed located 30-45 m below the No. 1 white ash that defines the base of the Skull Ridge Member (Figure B-1). Koning et al. (2002) identified two other white ashes underlying this thick ash, which they call the Nambé Member middle and lower white ashes. East of Nambé Pueblo, the Nambé Member lower white ash lies in the lower part of the fossiliferous portion of the Nambé Member and is overlain by approximately 50-100 m of poorly exposed strata of the Nambé Member (Galusha and Blick, 1971). The Nambé Member lower white ash was dated by Izett and Obradovich (2001) at 16.4 ± 0.13 Ma, which when converted yields a value of 16.6 ± 0.13 Ma. This value is consistent with geomagnetic interpretations of Barghoorn (1981 and 1985) (Figure B-1). The main Nambé white ash is 16.2 Ma based on the magnetic polarity data of Barghoorn (1981 and 1985) and Figure B-1.

Skull Ridge No. 2 white ash

Having a thickness of 10-150 cm, the No.2 white ash bed of the Skull Ridge Member (Galusha and Blick, 1971) is relatively easy to identify using subjacent and superjacent sediment.

Underlying sediment (interbedded siltstone and very fine sandstone) tends to be light brown and overlying sediment (interbedded siltstone and very fine to fine-grained sandstone) is commonly tan-colored (Appendix E). $^{40}Ar/^{39}Ar$ dating by Izett and Obradovich (2001), using only two sanidine and two biotite crystals, returned an age of 15.5 ± 0.07 Ma, which when converted yields a value of 15.7 ± 0.07 Ma. However, this seems slightly low considering that this ash lies relatively closely above (i.e., 27 m) a 15.97 Ma geomagnetic polarity reversal (Figure B-1; Ogg and Smith, 2004) and no signs of a disconformity or soil development is observed in the 27 m below this white ash. Therefore, we use a 15.8 Ma age for the Skull Ridge No.2 white ash, consistent with the 15.8 Ma age interpreted by Barghoorn (1981 and 1985) (Figure B-1).

Skull Ridge No. 3 white ash

The No. 3 white ash bed of the Skull Ridge Member (Galusha and Blick, 1971) is not quite as recognizable as the No.2 white ash, but it is locally quite thick (40-100 cm) and lies 15-20 m above No. 2 white ash bed. This ash was useful in this study because it was chemically correlated between the hanging wall and footwall of the Santa Clara-North Pajarito fault (Slate et al., 2013). Analyses of only two sanidine crystals returned an $^{40}Ar/^{39}Ar$ age of 15.4 ± 0.08 Ma, which when converted yields a value of 15.6 ± 0.08 Ma. Based on its proximity to the Skull Ridge No. 2 white ash bed, we prefer a value of 15.7 Ma (Figure B-1).

Skull Ridge No. 4 white ash

Like the Skull Ridge No. 2 white ash bed, the No. 4 white ash bed of the Skull Ridge Member is relatively easy to identify based on its thickness (70-170 cm thick east of Española) and because it is overlain by a tongue of pinkish sediment consisting of claystone, siltstone, and

very fine- to medium-grained sandstone. A 30 cm-thick, chalky white ash near the top of the lower Rio del Oso section (footwall of the Santa Clara-North Pajarito fault; sample RDO-091106a in Figure D-1 of Appendix D) is chemically similar to the Skull Ridge No. 4 white ash (Slate et al., 2013). East of Española, sanidine crystals from No. 4 white ash were dated by Izett and Obradovich (2001) at 15.3 ± 0.05 Ma, which when converted is 15.5 ± 0.05 Ma, and by McIntosh and Quade (1995) at 15.45 Ma ± 0.06 Ma (both used $^{40}Ar/^{39}Ar$ methods). We use an age of 15.4 Ma for the No. 4 white ash based on the relative position of this tephra in strata correlated to the C5Br polarity chron (Figure B-1).

285 Road ash

The 285 road ash listed in Izett and Obradovich (2001) coincides with the top of the Skull Ridge ash zone and likely corresponds to Ash Eta or Zeta of Galusha and Blick (1971). Being a distinctive gray color, we presume this ash correlates to the "Blue Ash" of the uppermost Skull Ridge Member that is depicted in Barghoorn (1985). Five sanidine crystals from this ash yielded a $^{40}Ar/^{39}Ar$ age of 15.1 ± 0.06 Ma, which when converted is 15.3 ± 0.06 Ma. Because this ash lies in sediment with normal geomagnetic polarity, it almost certainly must be younger than 15.16 Ma (Figure B-1). Therefore, we retain the 15.1 Ma age for this ash bed (Figure B-1).

Pojoaque white ash zone and the TW ash

Izett and Obradovich (2001) dated a discontinuous, thin, white tuff located about 3 m below a laterally continuous gray ash in the Pojoaque type section, which they call TW. The gray ash is noted as the "Blue gray tuff" in the Pojoaque Member by Galusha and Blick (1971) and as the "Upper blue-gray ash" by Barghoorn (1985). The resulting 13.7 ± 0.18 Ma $^{40}Ar/^{39}Ar$ age of

Izett and Obradovich (2001) for TW is consistent with the geomagnetic polarity and fossil data (Tedford and Barghoorn, 1993) (Figure B-1), but is inconsistent with zircon fission-track ages of 9.4 ± 0.9 Ma (two sigma) obtained on the overlying gray ash. We use the 13.7 ± 0.18 Ma because of its agreement with the fossil and geomagnetic polarity data. Note that the interpreted 13.2-14.0 Ma age for the entire Pojoaque white ash zone is reasonable, but not tightly constrained, when this age for the TW bed is integrated with the fossil data of Tedford and Barghoorn (1993) and the geomagnetic polarity data for the Pojoaque and Martinez sections (Barghoorn, 1981 and 1985) (Figure B-1).

Coarse white ash zone

A distinctive zone of coarse ashes lies above the Pojoaque white ash zone. These generally contain fragments of pumice, compacted white ash, and plagioclase crystals along with 1-10% biotite crystals, 3-7% pink to light gray, felsic to intermediate volcanic fragments, 3-5% quartz, and trace to 2% hornblende (Koning et al., 2007a). There are two approximate subdivisions of the coarse white ash zone. Coarse white ashes in the vicinity of Española lie at a stratigraphically low level near the base of the Cejita Member (west of the Rio Grande) and at the base of the Cuarteles Member (east of the Rio Grande). Dating of biotite from these lapilli and coarse ashes have yielded older ages (12-13.1 Ma; Appendix C and Koning et al., 2007a). Based on stratigraphic and geomagnetic relations on Figure B1, we use an age range of 12.0-13.0 Ma for the lower coarse white ash zone. Between the Buckman well field and Los Alamos, coarse ash and lapilli beds encompass a stratigraphically wide zone in somewhat younger strata of the Cuarteles Member. Here, the stratigraphically lowest known coarse ash yielded an $^{40}Ar/^{39}Ar$ age age of 10.9 ± 0.2 Ma (W. McIntosh and S. Cather, unpubl data for N.M.

Geochronology Research lab #6240), and it is likely that these coarse white ashes extend to ca. 8 Ma based on subsurface stratigraphic relations and dating of basalts under the Pajarito Plateau (Koning et al., 2007b and WoldeGabriel et al., 2006). Also, pumice lapilli from a 27 m-thick zone of coarse tephra interbedded in the Chamita Formation yielded a $^{40}Ar/^{39}Ar$ age of 11.08 ± 0.44 Ma (from biotite; Table 1 of manuscript, sample Unit-5c-NWChiliSect-djk). We refer to these younger tephra as the upper coarse white ash zone, and assign them an age range of 8.0-11.2 Ma. The lithologic character of tephra samples in the upper and lower coarse white ash zones are generally indistinguishable in hand sample.

Northwest of Española is a greenish coarse white ash-lapilli bed in a stratigraphic zone marked by interfingering of the Cejita and Vallito Members (Chamita Formation), which we informally call the upper green coarse white ash bed. In the vicinity of the Chamita stratotype (i.e., south end of Black Mesa), this bed lies immediately below a tongue of cross-stratified eolian sandstone. This eolian sandstone and the underlying green tephra bed were correlated across the Santa Clara fault. The tephra bed is too altered for successful radiometric dating. However, a similar greenish white ash-lapilli bed in this same stratigraphic interval was encountered in the West Chili stratigraphic section and lies between a dated tephra (11.08 ± 0.44 M; Koning et al., 2011) and a dated basalt (10.11 ± 0.13 Ma; Maldonado and Miggins, 2007) (Figure B-1; Appendix E). Considering its stratigraphic position midway between these two dated stratums, interpolation yields an approximate age of 10.6 Ma for the upper green coarse white ash bed (Figure B-1).

Alcalde tuffaceous zone

Stratigraphically above the lower coarse white ash zone and north of Española lies a tuffaceous interval about 50 m-thick (Koning et al., 2005a). It consists of three distinct stratums. The lowest stratum is laterally extensive and consists of one to two, thin to thick ash beds, black to gray in color, and mostly coarse-grained. These dark ashes are likely basaltic or basaltic andesite in composition. The middle stratum consists of a ~10 cm-thick bed of mixed, soft, gray to dark gray coarse ash and white coarse ash. The upper stratum contains a 2-20 cm-thick bed composed of coarse white ash and fine, white, pumiceous lapilli. It lies 1.5-2.0 m above a 120 cm-thick interval of ashy sand. The upper marker bed returned a $^{40}Ar/^{39}Ar$ age of 9.40 ± 0.46 Ma (Appendix C). Considering the error of this sample, we infer an age range of 9.0-10.0 Ma for the entire Alcalde tuffaceous zone and 9.4-10.0 Ma for the lower stratum. Note that the Alcalde tuffaceous zone appears to correlate with the upper coarse white ash zone.

Chamita lower and upper tuffaceous zone

In the Chamita stratotype lie two prominent tephra zones (Figure B-1). The lower tuffaceous zone is utilized in our study and is discussed below. The age of the Chamita upper tuffaceous zone is well-constrained at 6.8-6.9 Ma (McIntosh and Quade, 1995; Koning et al., 2004; Koning et al., 2005a). The Chamita lower tuffaceous zone is ~30 m-thick and has three subdivisions (Koning et al., 2004; Koning et al., 2005a): 1) one to two lower beds consisting of gray, coarse ash to fine lapilli (1-8 mm) of dacitic(?) composition; 2) one to two middle beds, spaced 3 m apart and located 9-15 m above the aforementioned lower beds, that contain a lower bed of altered, lapilli-size clasts (composed of consolidated white ash or pumice) overlain by an upper bed of white, coarse ash-fine lapilli with 7-20% gray (and minor pink, green, and black) dacite(?) lithic fragments 7-20 mm in length; and 3) a ledge-forming upper bed, 50-55 cm-thick,

consisting of pumiceous coarse white ash with 20% biotite and hornblende(?). A lower tephra in the Chamita lower tuffaceous zone yielded a 7.7 ± 0.3 Ma age from hornblende. However, the dated bed is located in reversed geomagnetic polarity strata (McIntosh and Quade, 1995) that lies between 8.3 and 8.8 Ma magnetic reversals (Figure B-1; Ogg and Smith, 2004). Integration of magnetic polarity data with the stratigraphic location of the Chamita lower tuffaceous zone (MacFadden, 1977; Ogg and Smith, 2004; Figure B-1) results in an age range of 8.1-8.7 Ma for the Chamita lower tuffaceous zone.

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Figure B-1.

COMPARISON OF RADIOMETRIC AGE CONTROL, TEPHROCHRONOLOGY, AND MAGNETIC POLARITY DATA

Stratigraphic correlations in the Santa Fe Group using available radiometric age control, tephrochronology, and magnetic polarity data (McIntosh and Quade, 1995; Izett and Obradovich, 2001; Barghoorn, 1981, 1985; MacFadden, 1977).

Composition

- Conglomerate — 7.7 ± 0.3 — Interpreted age (Appendix B)
- Sandstone — 7.7 ± 0.3* — $^{40}Ar/^{39}Ar$ age (Appendix B)
- Clayey-silty sandstone
- Siltstone
- Tephra & lava

Units

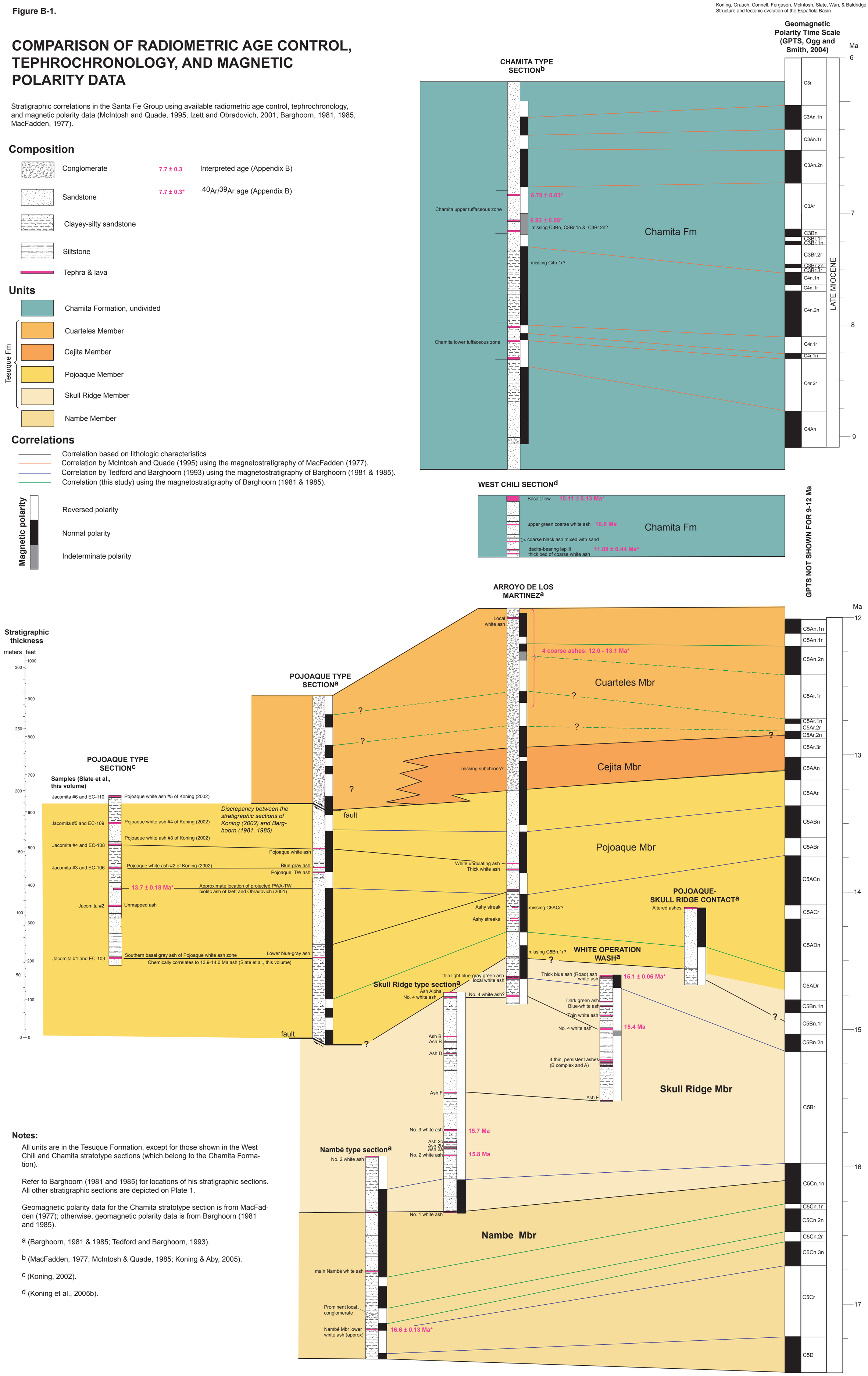
- Chamita Formation, undivided
- Tesuque Fm:
  - Cuarteles Member
  - Cejita Member
  - Pojoaque Member
  - Skull Ridge Member
  - Nambe Member

Correlations

- Correlation based on lithologic characteristics
- Correlation by McIntosh and Quade (1995) using the magnetostratigraphy of MacFadden (1977).
- Correlation by Tedford and Barghoorn (1993) using the magnetostratigraphy of Barghoorn (1981 & 1985).
- Correlation (this study) using the magnetostratigraphy of Barghoorn (1981 & 1985).

Magnetic polarity

- Reversed polarity
- Normal polarity
- Indeterminate polarity



Notes:

All units are in the Tesuque Formation, except for those shown in the West Chili and Chamita stratotype sections (which belong to the Chamita Formation).

Refer to Barghoorn (1981 and 1985) for locations of his stratigraphic sections. All other stratigraphic sections are depicted on Plate 1.

Geomagnetic polarity data for the Chamita stratotype section is from MacFadden (1977); otherwise, geomagnetic polarity data is from Barghoorn (1981 and 1985).

[a] (Barghoorn, 1981 & 1985; Tedford and Barghoorn, 1993).

[b] (MacFadden, 1977; McIntosh & Quade, 1985; Koning & Aby, 2005).

[c] (Koning, 2002).

[d] (Koning et al., 2005b).