

WESTWARD MIGRATING IGNIMBRITE CALDERAS AND A LARGE RADIATING MAFIC DIKE SWARM OF OLIGOCENE AGE, CENTRAL RIO GRANDE RIFT, NEW MEXICO: SURFACE EXPRESSION OF AN UPPER MANTLE DIAPIR?

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ABSTRACT: (Chamberlin et al., 2002)

A cluster of five large overlapping ignimbrite calderas is moderately well exposed in strongly extended tilted fault-block mountain ranges of the central Rio Grande rift, southwest of Socorro NM. The Socorro-Magdalena caldera cluster (SMCC) is 85 km long and 20-25 km wide. It parallels the southeastern flank of the Colorado Plateau and the WSW-trending San Agustin arm of the rift. Precise $^{40}\text{Ar}/^{39}\text{Ar}$ ages of sanidines from the rhyolite ignimbrites demonstrate that the distended calderas become progressively younger to the west-southwest. Large volume ignimbrite eruptions occurred at 31.9, 28.7, 27.9, 27.4 and 24.3 Ma. A large satellitic caldera, formed at 28.4 Ma, is located 20 km south of the main overlapping trend.

Moderately alkaline to sub-alkaline basaltic andesite and basalt dikes of Oligocene age (31-24 Ma, K-Ar, $^{40}\text{Ar}/^{39}\text{Ar}$ in progress) form a large semi-continuous radial array that is broadly focused on the SMCC. The Magdalena radial dike swarm (MRDS) fans through 220° of arc from Pie Town clockwise to Acoma, Chupadera, Bingham and Elephant Butte. The maximum radius of the MRDS is 125 km; subswarms of near parallel dikes are commonly 20-75 km long. Longer dikes are typically basaltic andesites (53 -56 wt. % SiO_2). Within the NW-striking Pie Town subswarm, exposed dike length (75, 24 and 2 km) decreases with increasing MgO content (3.1, 5.9 and 8.0 wt. %, respectively). This is consistent with dominantly horizontal flow and lateral intrusion of magma at different levels of neutral buoyancy, as controlled by magma density. Cross cutting relationships of undated dikes near Riley and La Joya imply a westerly migrating focus of mafic magmatism. Within 40 km of the northeast margin of the caldera cluster, rhyolite ignimbrites are intercalated with a 400-700 m thick plateau-like belt of basaltic andesite lavas. We suggest this 7000 km³ bimodal volcanic pile is the surface expression of a diapiric upwelling from the upper mantle that formed during westward retreat and disintegration of the Farallon slab in Oligocene time. Westward flow in the surrounding mantle may have tilted the rising diapir and sheared it into multiple segments, thus producing the apparent westward migration of magmatism in the overlying crust. The Socorro-Magdalena magma system exhibits characteristics similar to recently described "miniplumes".

INTRODUCTION

We present a testable working hypothesis that suggests long basaltic-andesite dikes exposed on the southeastern Colorado Plateau and southern Great Plains are linked at depth to a westerly younging cluster of Oligocene ignimbrite calderas in the Socorro-Magdalena region of the central Rio Grande rift. This moderate sized melt anomaly (~ 7000 km³) is referred to here as the Socorro-Magdalena magmatic system of Oligocene age. It is expressed by three mappable domains: 1) a core area of five large overlapping calderas (or cauldrons), 2) a medial apron of mafic lavas and intertonguing ignimbrite sheets, and 3) an outer fringe of radiating mafic dikes broadly focused on the westward migrating caldera cluster (Fig.1).

The hypothesis predicts that the age relationships of these radiating dikes will be consistent with a westerly migrating mafic source body underlying the caldera cluster. For example, NNE- and

NNW- striking dikes near Riley should show the NNE dikes cutting the NNW set, where they intersect. Likewise, subparallel dikes at Acoma, Hickman and Pie Town should become younger to the west, which is a trend already suggested by the published low-precision K/Ar data (Fig.1). Detailed mapping of dike crossing relationships and $^{40}\text{Ar}/^{39}\text{Ar}$ dating of the radial dike swarm are now underway; preliminary results seem favorable.

Thick piles of mafic lavas interleaved with ignimbrites occur on the flanks of the caldera cluster. Shorter radial dikes, including some mafic feeder dikes (Tonking, 1957), also occur near Riley on the north flank of the caldera cluster. These observations suggest the presence of a lower crustal mafic sill complex under the calderas. Presumably these mafic sills fueled generation of the large rhyolitic bodies that were erupted as ignimbrites. A sequentially rising chain of upper mantle diapirs, associated with retreat of the subducting Farallon slab, is hypothesized as a mechanism capable of producing the observed pattern of westerly younging calderas and peripheral mafic lavas.

BACKGROUND

The widespread occurrence of silicic ash-flow tuffs (ignimbrites), caldera-collapse structures (cauldrons) and radial dike patterns within and adjacent to the Mogollon-Datil volcanic field of southwestern New Mexico have been well known for nearly three decades (e.g. Elston, 1976). Decades of detailed geologic mapping in the Socorro-Magdalena region (Osburn and Chapin, 1983a, 1983b; and Ferguson, 1991), coupled with high-precision $^{40}\text{Ar}/^{39}\text{Ar}$ dating of sanidine separates from regional ignimbrites (McIntosh et.al. 1991; Chamberlin et.al., in press) have recently brought into focus the westward younging caldera cluster shown in Figure 1. In separate studies, prominent mafic dikes within the Colorado Plateau and Great Plains cratonic plates (Fig. 2, 2A, 2B) were dated by the K/Ar method. The results were interpreted in terms of regional stress domains, presumed to be of tectonic origin (Laughlin et. al. 1976, Aldrich et. al., 1986). Domains of least-principal horizontal stress were outlined using dikes of similar age; however, this procedure left many undated dikes, of various orientations, out of the pattern analysis.

In contrast, we have plotted essentially all available location, orientation and age data for mafic dikes in west-central New Mexico and then let the regional patterns be deduced from a more comprehensive data set (Fig.1). Data omitted here include about half the dikes exposed in the Riley and La Joya areas, which are too numerous to show at this scale; however the dominant trends are illustrated. With this approach, the radial distribution of Oligocene mafic dikes surrounding the Socorro-Magdalena caldera cluster becomes quite distinct. An obvious question then arises, is this radial dike pattern of magmatic origin or of tectonic origin, or both?

DIKES AS STRESS INDICATORS:

A dike is a magma-filled crack that propagates along a vertical plane in the direction perpendicular to the least principal horizontal stress *at the time of emplacement* (Rubin, 1995). We emphasize "time of emplacement" because stress fields can change rapidly. To paraphrase Dan McKenzie (1972), stress fields of continental tectonic plates are far too complex to understand in detail, one should just try to understand which way the plates are moving. Likewise we believe that the interaction of tectonic and magmatic stresses are far too complex to understand in detail, one should first try to understand which way the magma-filled cracks have propagated and determine the locus of the contemporaneous magmatic center that represents a reasonable source. With this approach, reliable geochronology (relative and radiometric) is an obvious requirement for meaningful interpretation of tensile stress patterns recorded by dikes in ancient volcanic terranes.

Radial dike swarms represent the time (and space), when magmatic pressures have overwhelmed regional stresses of plate tectonic origin. Length scales of radial dike swarms range from ten to over one thousand kilometers (Ernst et.al. 1995). Studies in Iceland conclusively demonstrate that some dikes propagate upwards and outwards, as elliptical fracture fronts, away from a central shield volcano (Sigurdsson, 1987). Similar observations in many other magmatic terranes negate the common notion that mafic dikes must lie directly above their source.

NNW to NNE- trending mafic dikes in the Riley area (~27-29 Ma, Fig.3) are more closely spaced and abundant than elsewhere in the MRDS. Also, they were emplaced contemporaneous with north-trending high-angle normal faulting in the nearby Joyita Hills, Lemitar Mountains and eastern San Mateo Mountains (~32-24 Ma, e.g. Chamberlin, 1983; Ferguson, 1991). This is a strong correlation of westward early rifting and east-west dike dilation within the southeastern corner of the Colorado Plateau. In comparison, north-trending normal faults that bound Neogene rift basins near Pie Town (Omega Basin) and Bingham (Fig.1) cut across the radial dikes at a high angle, thereby indicating that the Oligocene dikes in these areas were not emplaced orthogonal to the long-term direction of tectonic extension

MAP DATA:

Data presented on Figure 1 are derived from many sources. Many features were compiled from the soon to be published Geologic Map of New Mexico (NMBGMR, 2003) and the NMGS Highway Geologic Map of New Mexico, currently in preparation (scale: 1:1,000,000). A complete set of references used in the compilation of Figure 1 is available on request from the senior author.

Ignimbrite Calderas:

Caldera cores are primarily defined by kilometer-thick sections of densely welded ignimbrite (Osburn and Chapin, 1983b). Margins of calderas are marked by intravolcanic unconformities at caldera walls and ring-fracture rhyolite lava domes or intrusions around the subsided cauldron block. Strongly tilted fault blocks of the Rio Grande rift, which are superimposed on the calderas, provide cross-section views of the caldera structures across a large range in erosion levels.

Mafic Lavas:

Thick piles of basaltic andesite lava flows and intercalated Oligocene ignimbrite sheets are exposed in tilted fault block ranges north and west of Socorro. Individual basaltic andesite flows are commonly 7-10 m thick; multiple flows between ignimbrites have an aggregate thickness of as much as 330m. These tongues of Oligocene mafic lavas are assigned to the La Jara Peak Basaltic Andesite in the Socorro region (Osburn and Chapin, 1983a). Small phenocrysts of olivine, altered to reddish brown iddingsite, are typical. Phenocrystic plagioclase, indicative of differentiation at depths less than 30 km (Wilson, 1989), is typically absent. Oligocene mafic lavas range from subalkaline basalt to moderately alkaline basaltic trachyandesite (Fig. 4). A primitive trachybasalt in the SE moat of the Socorro caldera (~31 Ma; Chamberlin et.al., in press) contains 9.3 % MgO and 170 ppm Ni; this suggests a relatively hot source zone in the upper mantle, compared to most subduction related basalts (Campbell, 2001).

Mafic dikes:

Locations and azimuths of mafic dikes shown on Figure 1 were verified using 1:24,000 topographic maps or orthophoto quadrangles where available. As shown, dike widths are exaggerated

and the lengths of some shorter isolated dikes are exaggerated to make them more visible. Numerous short dikes in the Riley and La Joya areas cannot be shown at this scale.

Mafic dikes are 1 to 75 km long, most are near vertical and range from 1 to 10m thick. They commonly display en echelon segments and occasionally exhibit what appear to be branching relationships. Narrow resistant chilled margins are typical of most dikes. Ridge-forming dikes occur in poorly indurated sandstones and shales; neutral to recessive dikes are commonly found in resistant sandstones, limestones, and volcanic host rocks.

Dikes of the Pie Town subswarm exhibit outcrop lengths proportional to their composition; the longest dike is the least mafic and the shortest dike is the most mafic (Baldrige et.al., 1989). These relationships are attributed to dominantly lateral propagation as controlled by relative buoyancy; this is illustrated in the transverse cross sectional model shown at the end of this poster.

Mafic dikes range from moderately alkaline trachybasalt to basaltic trachyandesite and subalkaline basaltic andesite (Fig. 4). They are commonly fine grained or diabasic, medium to dark gray, and often contain microphenocrysts of olivine, which may be altered to iddingsite. Phenocrystic plagioclase is typically absent. Longer dikes at Acoma, Hickman and Pie Town tend to be more titanium and phosphate-rich than contemporaneous dikes and lavas in the Socorro region (Laughlin, 1976); mafic dikes east of the Rio Grande tend to be more soda rich. Some northeast-trending dikes near Riley contain partially assimilated granitic xenoliths.

VOLUMES OF ERUPTIONS:

Estimated volumes of mafic lavas and intercalated ignimbrites are summarized on Figure 5. Intracaldera lavas of intermediate to silicic composition (not shown here) total about 400km³. Ages of mafic lava units are estimated as midpoints between bracketing ignimbrites. The thickest tongue of mafic lavas (330m) occurs between the 27.9 and 27.4 Ma ignimbrites in the Joyita Hills, Lemitar Mountains and southern Bear Mountains. This 27.7-Ma tongue represents the maximum eruption rate of Oligocene mafic lavas in the Socorro region (Fig. 6A). The zenith in rate of mafic lava eruptions is contemporaneous with the maximum rate of domino-style rotation of early rift fault blocks (Fig.6B; Chamberlin, 1983) and the maximum rate of westward migration of the caldera cluster (Fig.6C). These observations imply that basaltic eruptions are favored by relatively rapid rates of tectonic extension where the brittle-ductile transition zone is relatively deep. The total erupted volume of the Socorro-Magdalena magmatic system is approximately 7000km³, which is about 1/100 th of large igneous provinces associated with deep mantle plumes (Campbell, 2001).

PRELIMINARY TESTS OF THE HYPOTHESIS:

Detailed maps and photographs of intersecting dikes in the La Joya and Riley areas are shown on Figures 7A, 7 B, 7C, 7D, and 7E. These field observations provide a preliminary test of our hypothesis. Three digit azimuths of dikes are a convenient means of identifying the individual dikes or dike segments.

Field relationships support the interpretation of a moderately rotated basaltic-andesite feeder dike (037) near La Joya (Figs. 7A, 7B). This short, NE-trending feeder dike erupted at approximately 32 Ma; it appears to radiate from the 31.9 Ma Socorro caldera (Fig.1). A younger ENE-striking mafic dike locally offsets the feeder dike about 2 m to the left and also cuts the tephra unit associated with the feeder dike.

Limited observations of intersecting and branching mafic dikes south of Riley (Figs.7C, 7D, 7E) appear to show mutually cross-cutting relationships; this suggests a complex interaction of tectonic and magmatic stress fields. A NNE-striking, xenolith-bearing mafic dike (017 to 007) appears to be

deflected where it crosses an older north-striking diabase dike (002 to 358). Where the two dikes are contiguous, they exhibit three resistant chilled margins; the narrower dike clearly occurs on the east margin of the dike pair. In the same area, a NNE-striking dike (027), which recently yielded an $^{40}\text{Ar}/^{39}\text{Ar}$ age of 28.12 ± 0.12 Ma, appears to branch from a similar looking mafic dike that strikes NNW (349). Further north this undated dike (349) appears to offset a narrow NNE-striking dike (025) by about 2 m. Exposures are not good here; it is possible that the NNE-striking dike is younger and refracted where it crosses the NNW trending dike. More field work and sampling are appropriate here.

Crossing dikes recently observed southwest of Riley (Fig. 7C, 7D) suggest that a propagating mafic dike can be strongly deflected where it intersects a preexisting dike at a moderate angle. A NE-striking biotite-bearing minette dike (059 to 032) clearly cuts across a NNE-striking diabase dike (011) here; however, an en echelon segment of the biotite-bearing dike also makes a sharp 70° bend where it approaches the older diabase dike. The above preliminary observations of cross-cutting dikes, where unambiguous, appear to support the model of a westerly migrating mafic source.

A newly determined $^{40}\text{Ar}/^{39}\text{Ar}$ age of the NNE-striking dike south-southeast of Riley (27.52 ± 0.15 Ma) is more consistent with its orientation and location than the previously published K/Ar age of 24.3 ± 0.8 Ma (Aldrich et.al, 1986). Regional map data imply that NNE-striking dikes near Riley were most likely associated with mafic sources under the 28.7-Ma Sawmill Canyon caldera and/or the 27.9-Ma Hardy Ridge caldera. New $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 27.5 to 28.1 Ma (Fig. 1) support this interpretation. An initial attempt to determine the $^{40}\text{Ar}/^{39}\text{Ar}$ age of the prominent NNW-striking dike southwest of Riley was unsuccessful; its published K/Ar age of 24.8 ± 0.6 Ma (Aldrich et. al. 1986) seems much too young for its azimuth. Figure 8 shows a graphic summary of published Ar-Ar age data for ignimbrites erupted from the Socorro-Magdalena caldera cluster and lower precision K-Ar data for mafic dikes of the surrounding Magdalena radial swarm. New Ar-Ar data for dikes at Riley (black peaks) clearly show they are contemporaneous with the maximum rate of rhyolite magma generation as expressed by relatively "rapid-fire" caldera-forming eruptions.

PRELIMINARY MODELS:

Most aspects of the transverse cross sectional model (Fig. 9) have been described above. Projections of the mafic dikes shown on Figure 1 commonly intersect about 10 km north of the caldera cluster; this suggests that the inferred lower crustal mafic sills are larger in diameter than the overlying calderas. The absence of plagioclase phenocrysts in the basaltic andesite lavas implies differentiation at depths greater than 30 km (Wilson, 1989).

Diapirs are derived from unstable boundary layers that contain material more buoyant than the overlying rocks (Olson, 1990). A stationary boundary layer produces diapirs that rise in random sequence. A steady relative motion between the diapir source and its surrounding matrix will produce a sequentially rising diapir chain. In a similar fashion, shearing of a diapir conduit will cause it to break up into a secondary diapir (Whitehead and Helfrich, 1990). We suggest that a sequentially rising diapir chain associated with rollback of the Farallon slab is a reasonable mechanism to produce the observed westerly migrating ignimbrite calderas (see cartoons in Fig. 10 A and 10B). Two slightly different models are suggested. One model (Fig 10A) depicts segmentation of a single diapir by westward differential shear in the surrounding upper mantle; the other model (Fig. 10B) depicts the effect of a west-migrating source zone that feeds multiple diapirs in sequence.

CONCLUSIONS:

- Oligocene mafic dikes (~32-24 Ma) of the Magdalena radial dike swarm (MRDS) are broadly focused on the westward younging Socorro-Magdalena caldera cluster (SMCC), which is exposed in tilted fault-block ranges of the central Rio Grande rift.
- Ignimbrites, intercalated mafic lavas, intracaldera lavas and radiating dikes of the Socorro-Magdalena magmatic system have a total volume of about 7000 km³, which is about 1/100 th of that in a large igneous province associated with a deep mantle plume.
- The maximum eruption rate of mafic lavas is contemporaneous with the maximum rate of domino-style extension in the early Rio Grande rift and the maximum rate of westerly caldera migration.
- Spatial, temporal and compositional data imply that mafic dikes radiating from the Socorro-Magdalena caldera cluster are linked at depth with a westerly migrating mafic sill complex in the lower crust.
- The common absence of phenocrystic plagioclase implies that the differentiated basaltic andesite magmas formed at depths greater than 30km, in the lower crust.
- A sequentially rising diapir chain, associated with rollback of the Farallon slab, is suggested as a mechanism that can explain the westward migration of the Socorro-Magdalena caldera cluster and its associated peripheral mafic magmatism.

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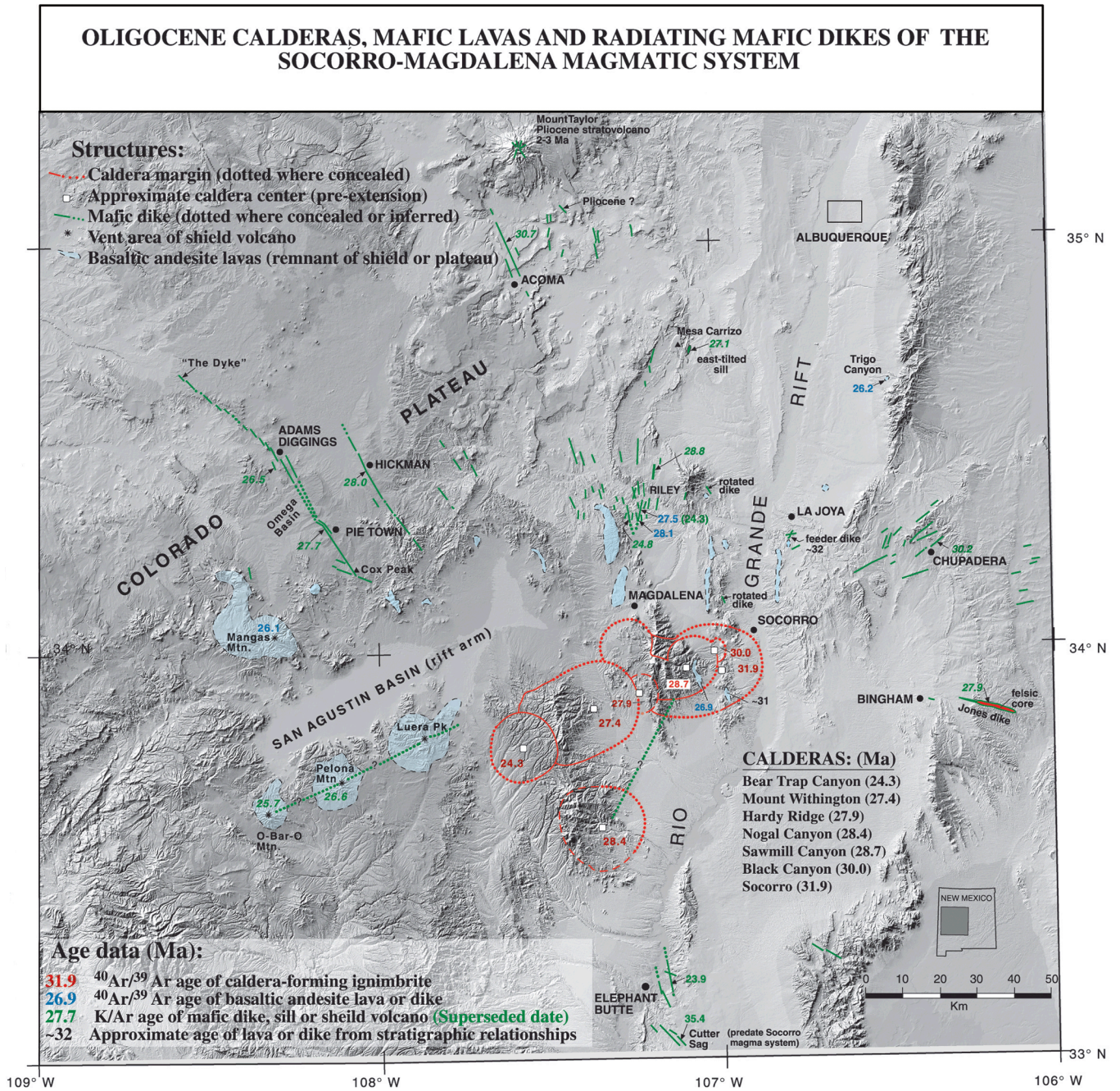
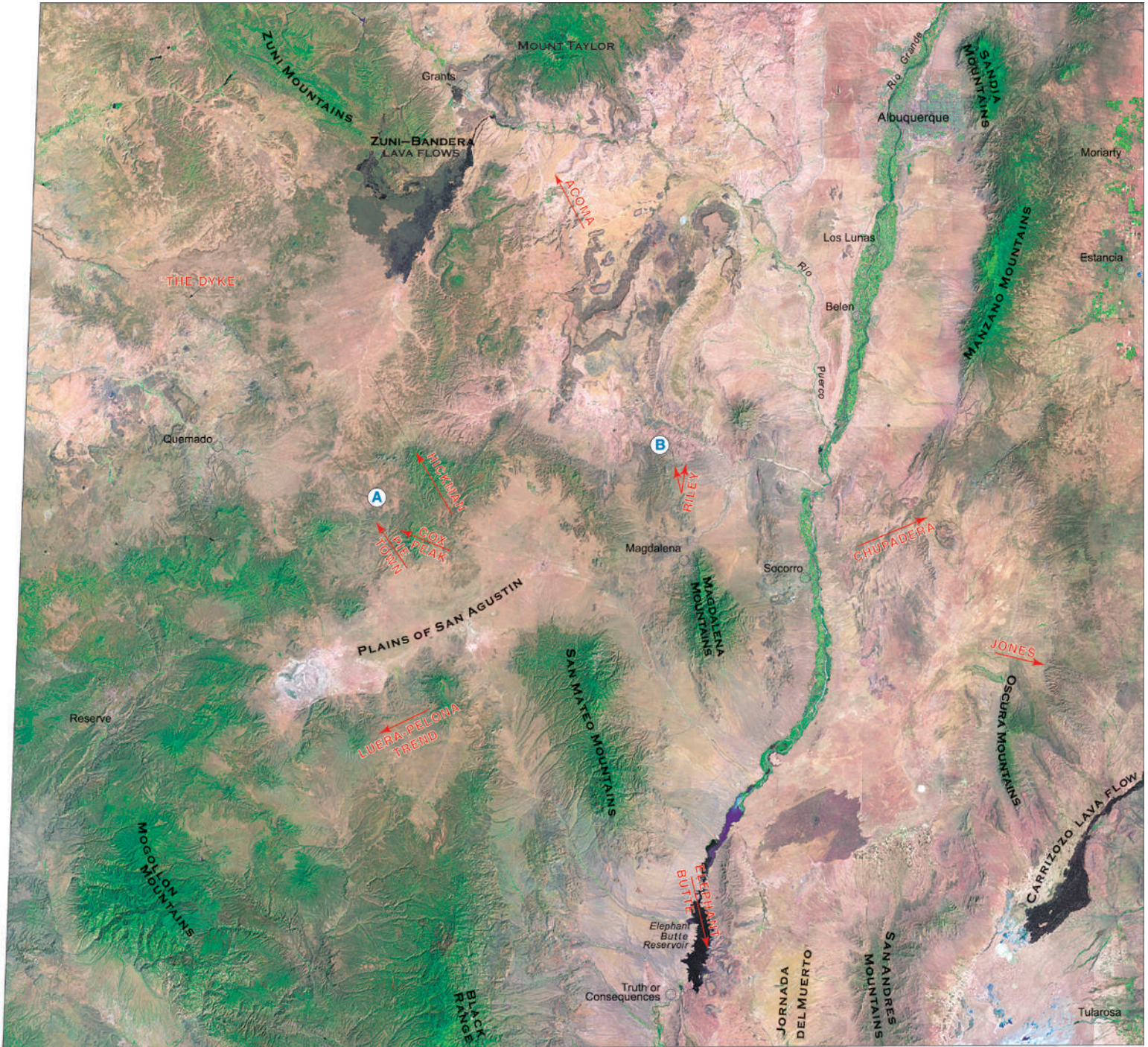


Fig. 1

Fig.2 LANDSAT IMAGE SHOWING MAJOR DIKE TRENDS OF THE MAGDALENA RADIAL DIKE SWARM



DIKE PHOTOS



Fig.2A. Hogback-forming mafic dike at Pie Town bends to left and disappears under the Miocene Omega Basin; looking NW.



Fig.2B. Looking SSE along prominent dike of the Riley subswarm. Sawmill Canyon caldera (28.7 Ma) underlies crest of Magdalena Mountains on the far horizon

Fig.3 LANDSAT IMAGE SHOWING CONVERGING DIKES
IN THE RILEY SUBSWARM



Fig. 4 Alkali-silica Classification of Mafic Dikes and Lavas

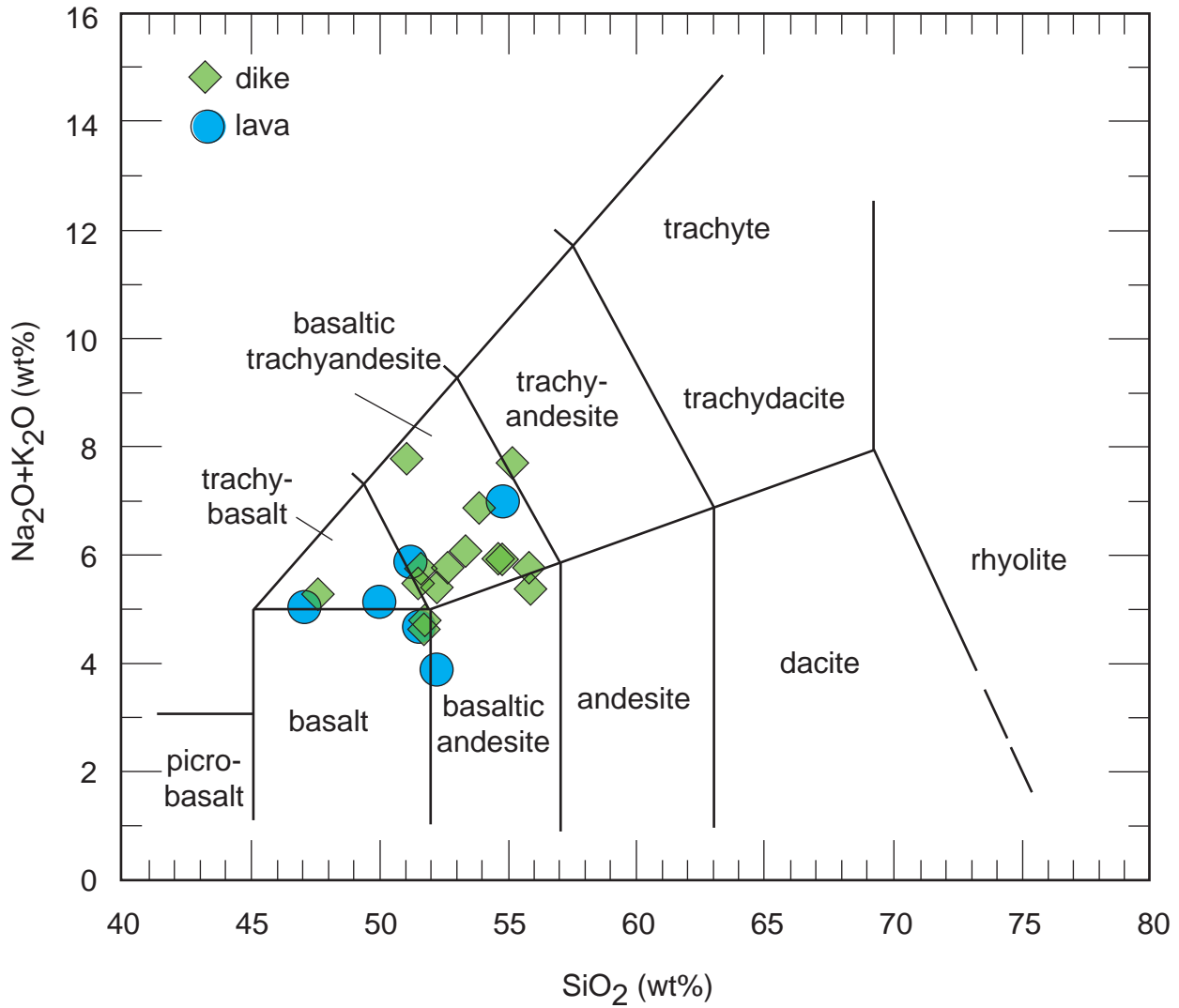


Fig.5 VOLUMES OF IGNIMBRITES AND MAFIC LAVA UNITS

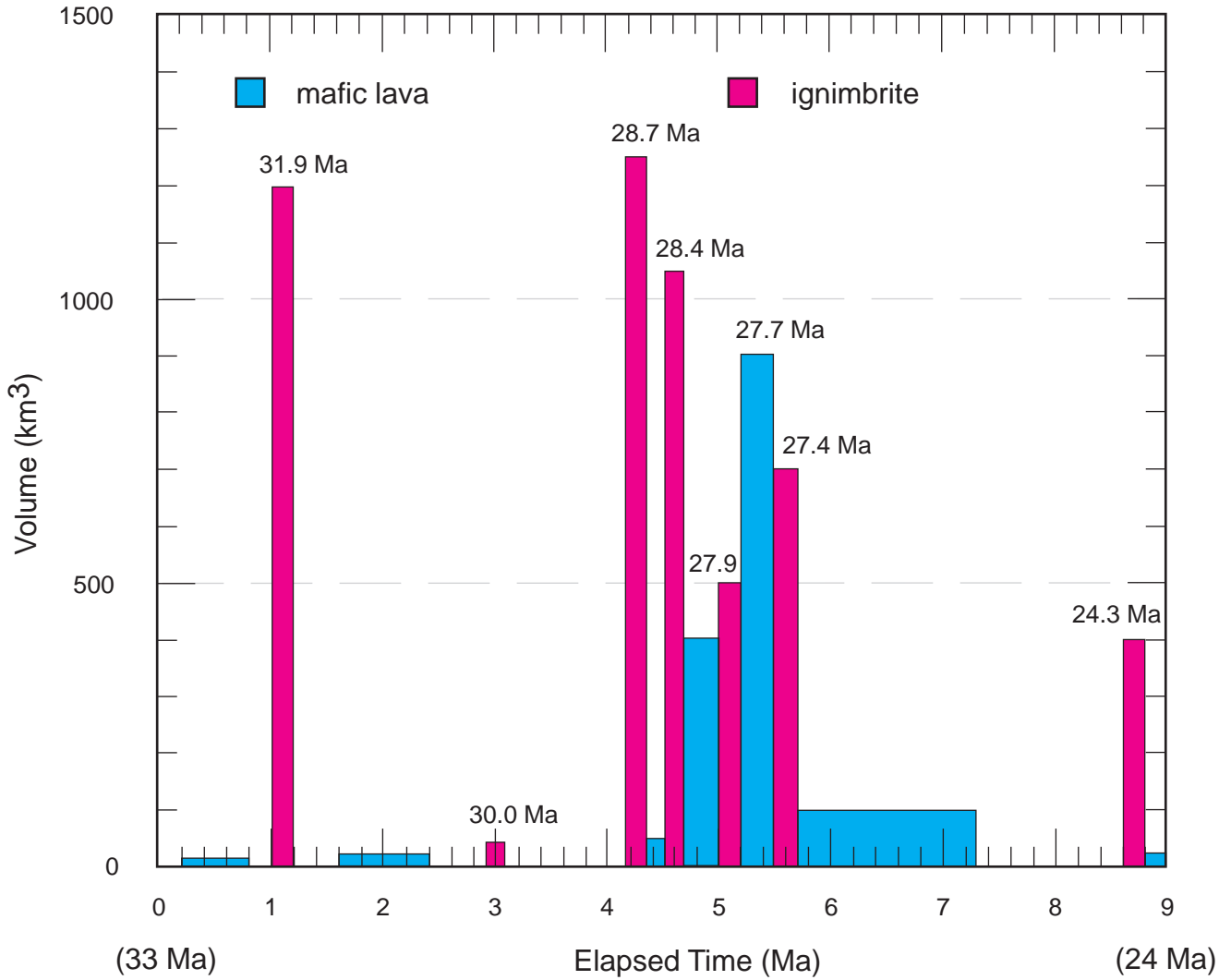


FIGURE 6: ERUPTION RATE OF MAFIC LAVAS VS. TECTONIC TILT AND CALDERA MIGRATION RATE

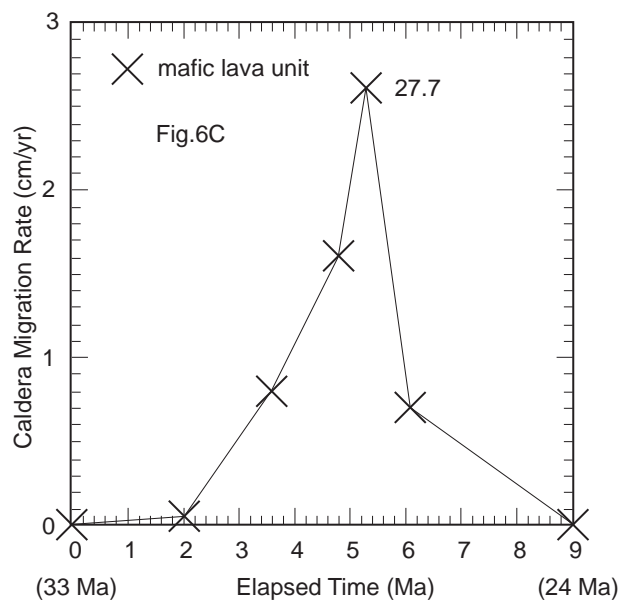
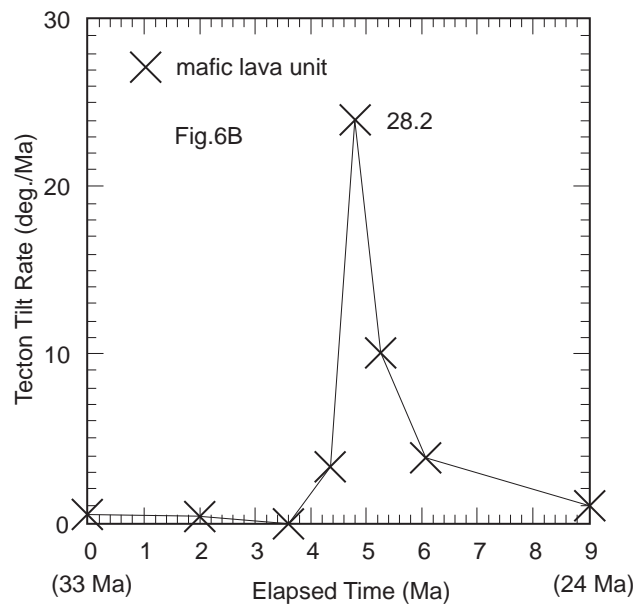
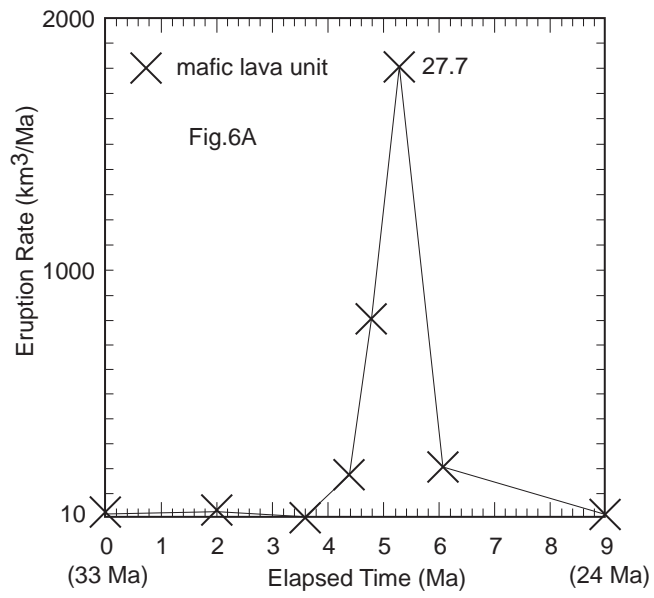


Fig. 7A Rotated Feeder Dike Near La Joya

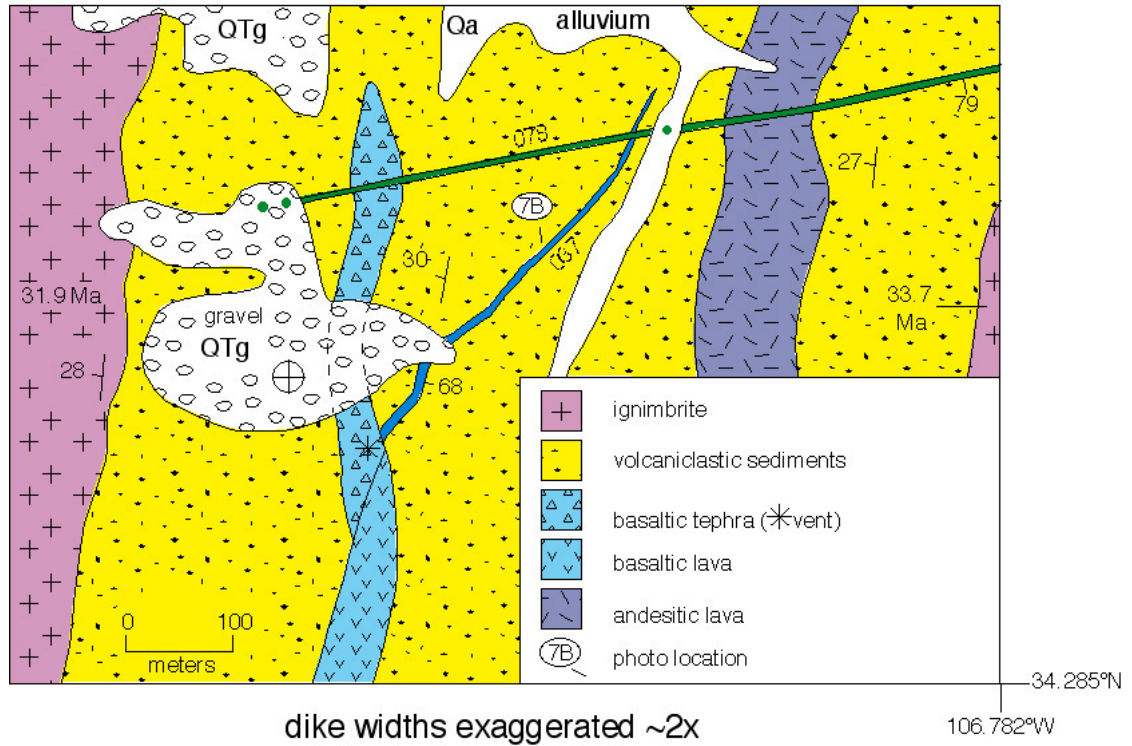
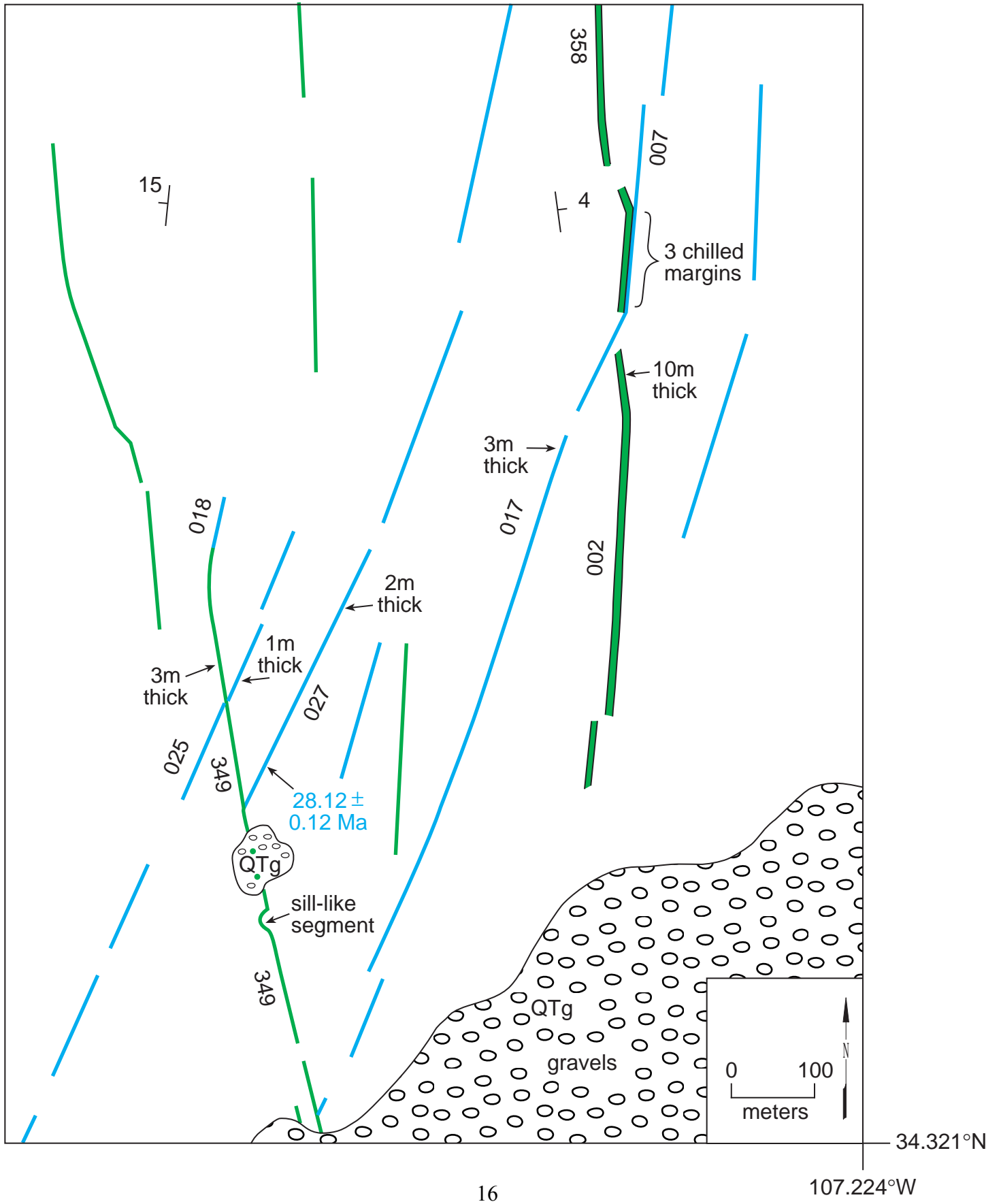


Fig. 7B. Looking SW along rotated feeder dike near La Joya. Upper Santa Fe gravels on horizon bury the dike and east-tilted volcaniclastic sandstones of the Spears Fm. form the host rock.

Fig.7C INTERSECTING DIKES SOUTH OF RILEY



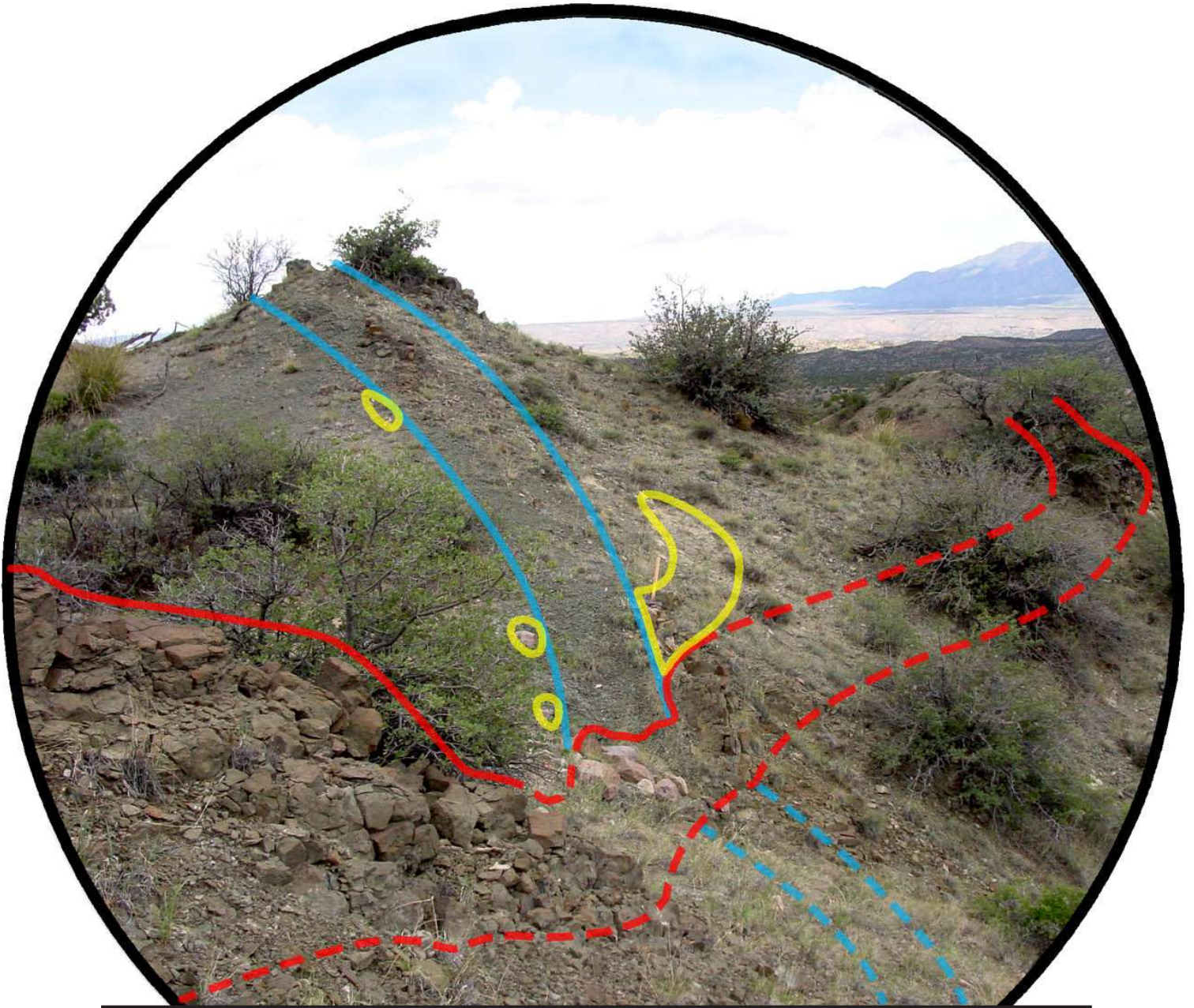
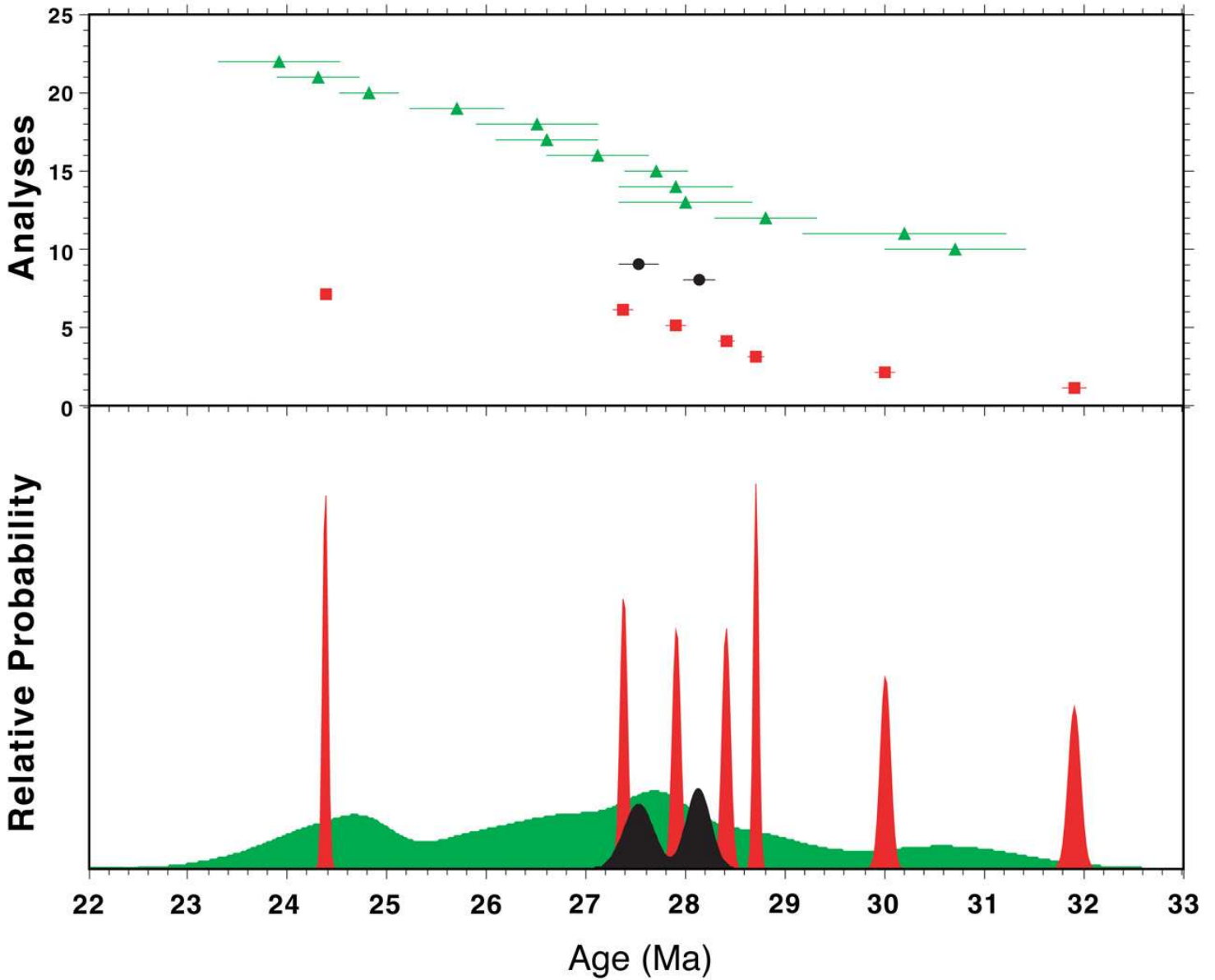


Fig. 7E. NE-striking, brownish-gray minette dike (red outline) cuts across a NNE-striking, medium gray, diabase dike (blue outline), all within outcrops of the Baca Formation (yellow outlines). Ladrón Peak is on the horizon

Fig.8. GEOCHRONOLOGY OF IGNIMBRITES AND DIKES



Ar-Ar ignimbrites (red), Ar-Ar dikes (black), K-Ar dikes (green)

Fig.9. TRANSVERSE CROSS SECTIONAL MODEL OF THE SOCORRO-MAGDALENA MAGMATIC SYSTEM AT ~ 28 Ma

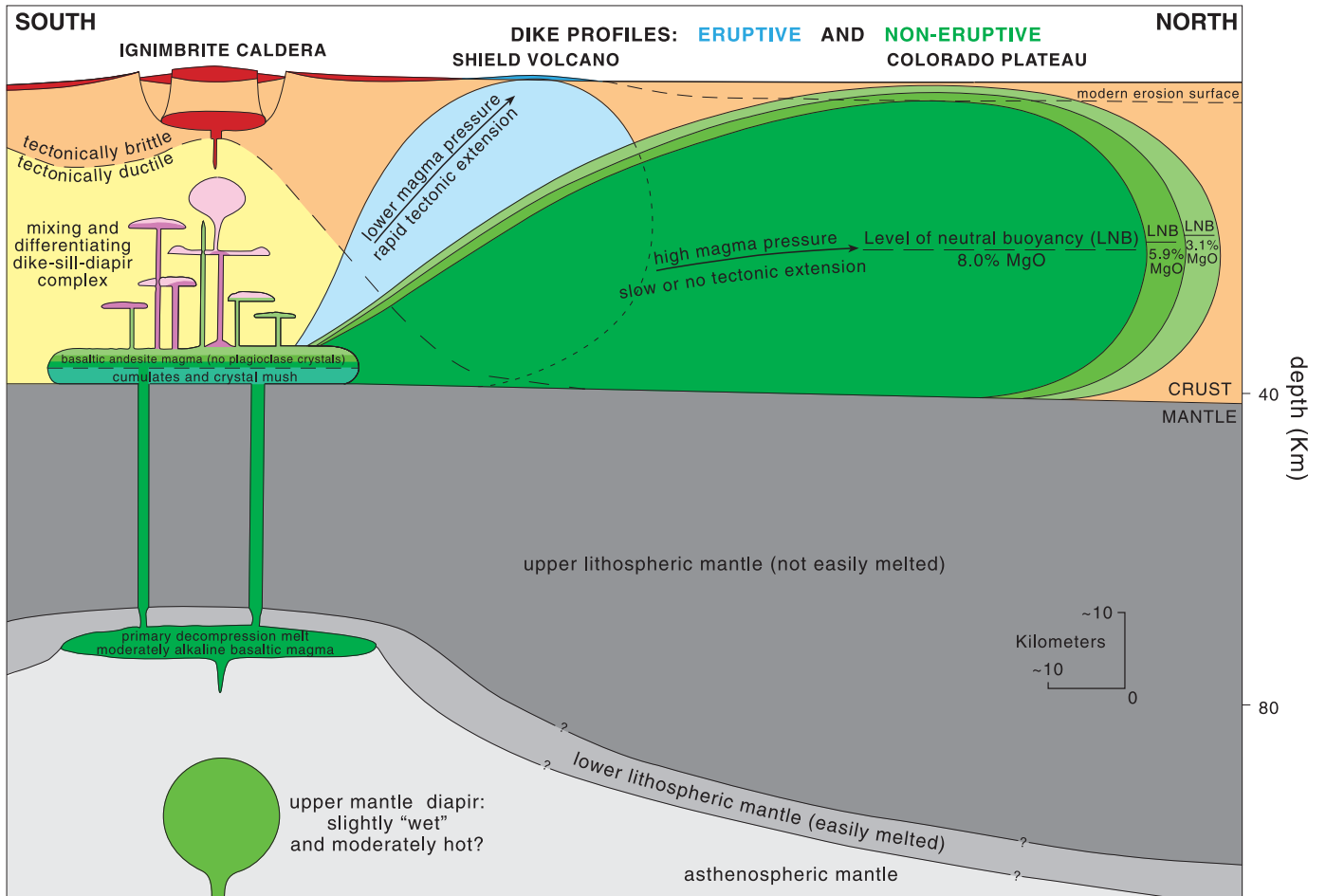
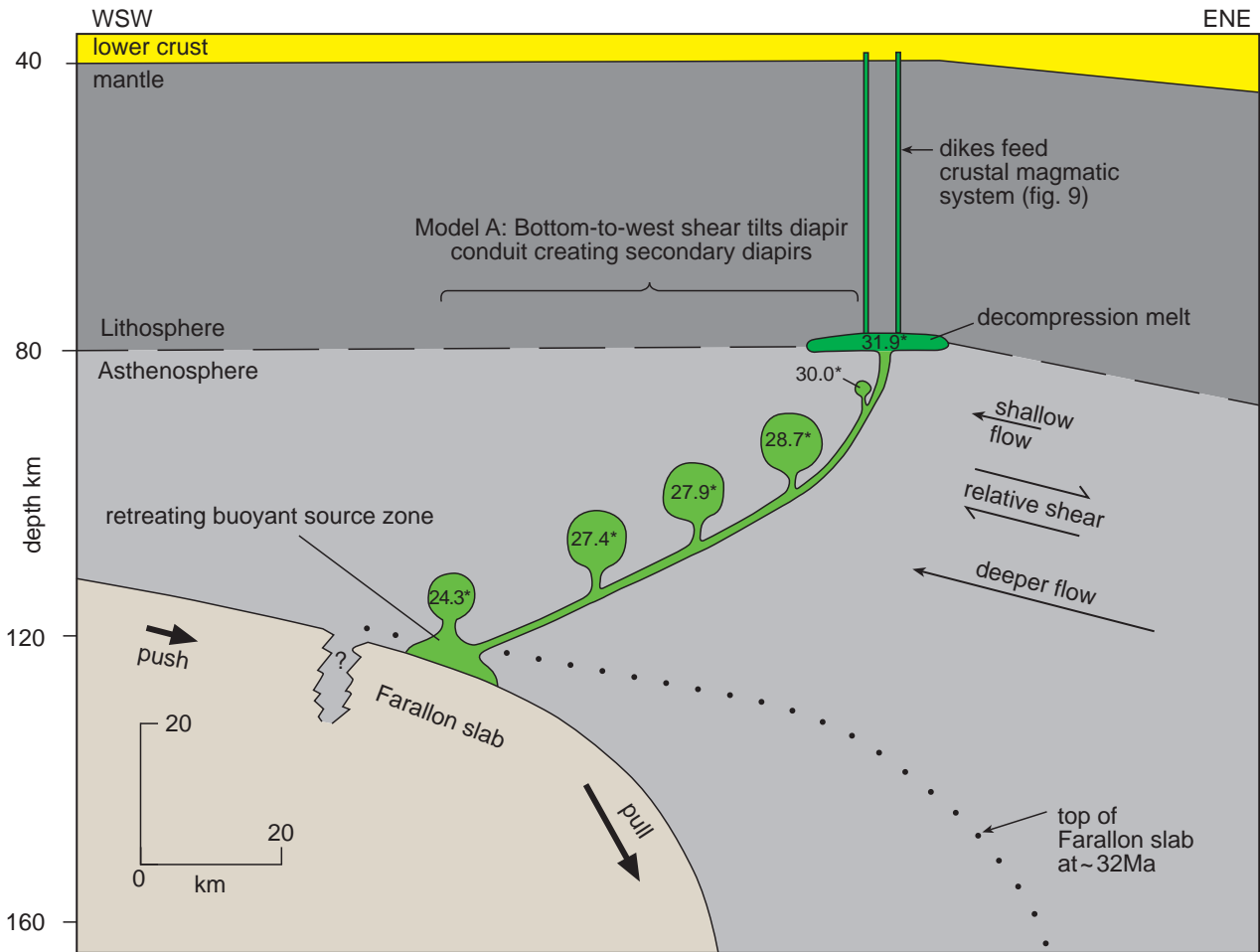
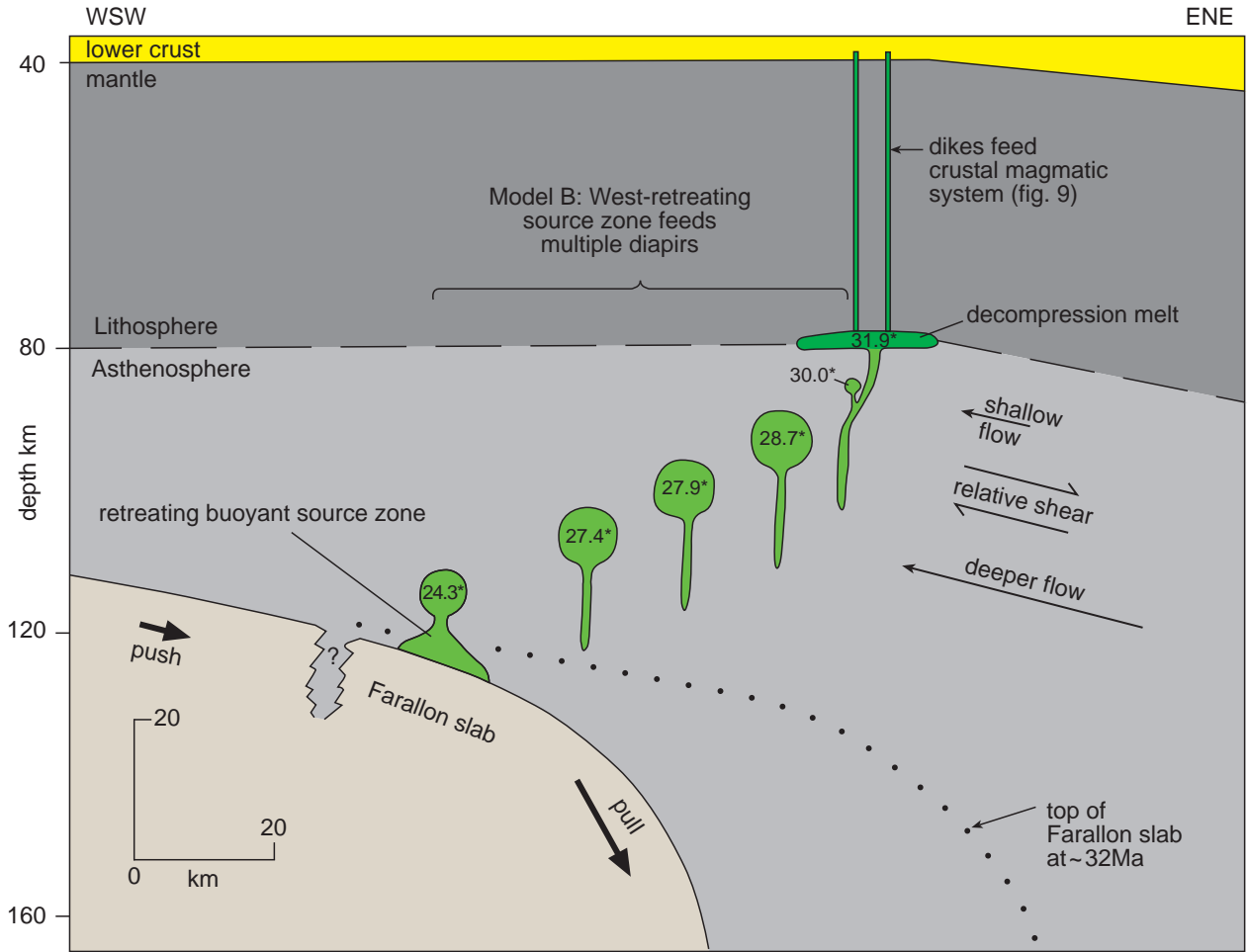


Fig.10A. LONGITUDINAL CROSS SECTIONAL MODEL OF UPPER MANTLE DIAPIR CHAIN ASSOCIATED WITH ROLLBACK OF THE FARALLON SLAB



*Numbers indicate the presumed link between an ignimbrite caldera (age in Ma) and a particular diapir

Fig.10B. LONGITUDINAL CROSS SECTIONAL MODEL OF UPPER MANTLE DIAPIR CHAIN ASSOCIATED WITH ROLLBACK OF THE FARALLON SLAB



*Numbers indicate the presumed link between an ignimbrite caldera (age in Ma) and a particular diapir