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Paleomagnetism of the latest Cretaceous-Paleocene intrusive suite of the Mezcala district, southern Mexico

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Paleomagnetic data from three plutons of the latest Cretaceous to early Tertiary Mezcala intrusive suite, of the Mezcala mining district in northern Guerrero State, in southern Mexico, are characterized by well-defined near univectorial magnetizations of both normal and reverse polarities. The magnetizations reside primarily in a ferromagnetic cubic phase (magnetite or maghemite) and partly in hematite. Within-site dispersion is relatively small, but between-site dispersion is not. The overall mean for 9 selected sites is of D=318.5° and I=47.1° (k=18.5; α_{95}=12.3°), and is discordant with respect to the reference direction for North America. The discordance may be explained by tilt down-to-the-northeast of the structural block that contains the intrusive suite of about 40° about a NW-SE trending axis, or perhaps more likely and based on additional geological evidence, by a combination of ∼20° of counterclockwise rotation about a vertical axis and a smaller amount of tilt. Vertical-axis-rotation is supported by paleomagnetic data from nearby localities, whereas a small magnitude of tilt is supported by geological field relations. This result is consistent with the hypothesis that Laramide structures of the Guerrero-Morelos platform were reactivated by a younger deformation event, and that there is a deformation event superimposed that involves lateral slip. The contrasting orientation of NW-SE trending structures within the Mezcala mining district affecting the plutons, and N-S trending Laramide structures, suggests that the discordant paleomagnetic directions are best explained by a combination of tilt and rotation.
Key words: Paleomagnetism, Laramide, Guerrero, Mexico.

1. Introduction

In southern Mexico there are two relatively recent events of deformation, one linked to the late Cretaceous Laramide orogeny and a younger one linked to strike-slip tectonics and truncation of the Pacific margin; the events are superimposed in the region of the Guerrero-Morelos platform (Fig. 1; Cerca-Martínez *et al.*, 2004; Meschede and Frisch, 1988). Unraveling the structural evolution of this region is thus difficult. Four apparently discrete magmatic pulses from Jurassic (?) to Miocene time affected the region as well, and they provide the means to date and perhaps separate the effects of Laramide from younger tectonic events. A suite of calci-alkaline stocks with associated skarn mineralization intrudes folded Cretaceous strata of the Morelos and Mezcala Formations in northern Guerrero State. The plutons have been associated with a Late Cretaceous volcanic arc formed in response to subduction of the Farallon plate along the western Mexico margin. Emplacement occurred after accretion of the Guerrero terrane or after cessation of Laramide-age compressional deformation (Morán-Zenteno *et al.*, 1999). The Mezcala granitoids (Fig. 2) are also host to economic Fe and Au mineralization (González-Partida *et al.*, 2003). The main deposits in the Mezcala district currently in exploitation are Filitos, La Agüita and Nukay; Bermejal is a prospect with 1,000,000 ounces of gold reserves.

Here we present paleomagnetic data for three of the intrusions of the Mezcala district. These data provide the means to recognize and quantify deformation that may be manifest as discordant paleomagnetic directions (Butler, 1992). Declination-only anomalies generally indicate rotations about a vertical axis; a combined anomaly, that is anomalies in both declination and inclination, indicate rotations (tilts) with respect to a horizontal axis; inclination only anomalies can be interpreted as either latitudinal displacement or tilt about a horizontal axis perpendicular to the expected (=observed) declination. If these rotations can be placed in a temporal sequence, the effects of distinct tectonic environments may be recognizable. We thus carried out a paleomagnetic study of the Mezcala intrusive suite in order to establish with reasonable certainty whether or not the plutons record significant deformation related to a late phase of Laramide deformation or a younger deformation event related to strike-slip motion along the southern Mexico Pacific margin. The paleomagnetic method has been applied with relative success to Laramide age intrusions to study the structural history various parts of the western United States (e.g., Melker and Geissman 1997; Hagstrum and Sawyer, 1989).

Strike-slip kinematics in southern Mexico have been related to displacement of the Chortis block along the Pacific margin in mid-Tertiary time (Morán-Zenteno *et al.*,

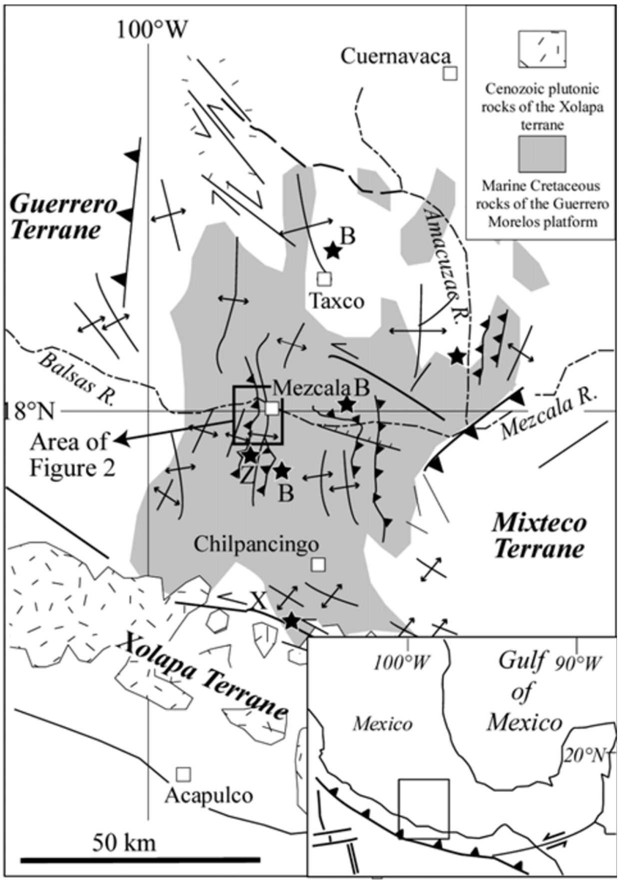

Fig. 1. Simplified tectonic map of southern Mexico showing the location of the Mezcala mining district region. Also included are the trends of the main Laramide structures, the extent of the Guerrero Morelos platform, and Cenozoic plutonic rocks. The map includes tectonostratigraphic terranes in southern Mexico and the location of additional paleomagnetic sampling localities (solid stars) mentioned in the text: B=Balsas Formation; Z=Zopilote canyon; X=Xaltianguis.

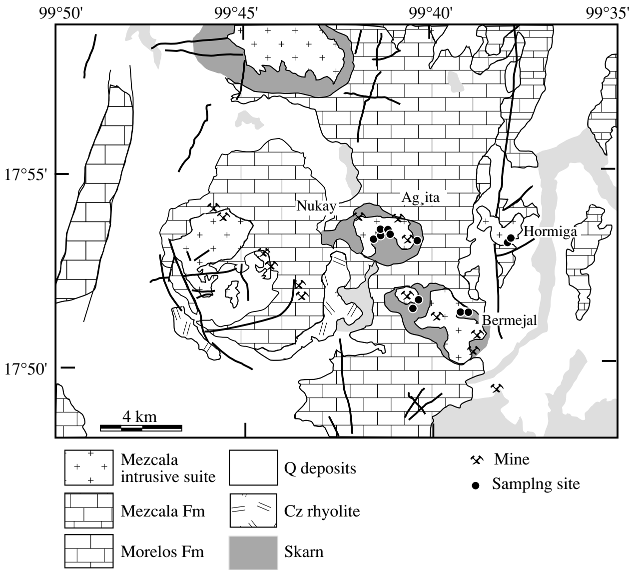

Fig. 2. Simplified geologic map of part of the Mezcala mining district, after Levresse *et al*. (2004). The locations of all paleomagnetic sampling sites are also given as black circles.

1999). Because the effects of Laramide deformation and mid-Tertiary strike-slip deformation are superimposed in areas of the Guerrero-Morelos platform, previous studies in Cretaceous rocks have been inconclusive in assigning rotations about a vertical axis to one of the deformation or to both (Molina-Garza *et al*., 2003). Thus, the study of the Mezcala intrusive suite would allow us to better constrain the timing and mechanism of counterclockwise rotation recorded by synfolding magnetizations in the Morelos and Mezcala Formations, about 20 kilometer south of the Mezcala mining district (Fig. 1). Similarly, paleomagnetic data for the intrusions would allow us to better understand rotations interpreted from data for continental detrital rocks of the Balsas Formation in the Taxco area (Urrutia-Fucugauchi, 1983) and concordant directions in the Balsas Formation in other localities of the Morelos-Guerrero platform (Molina-Garza and Ortega-Rivera, 2006). Paleomagnetically determined tilt or rotation might also be a useful tool for exploration and better understanding of the ore deposits.

2. Geologic Setting

The Mezcala intrusive suite includes several small bodies, most of them less than about 2 km in diameter (Fig. 2). Interpreted volcanic equivalents are the andesites of the Tetelcingo Formation (Ortega-Gutiérrez, 1980; Cerca-Martínez, 2004). Levresse *et al*. (2004) reported geochemical data for the intrusive suite, mineral alteration zone, and ore bodies; these authors also published U-Pb dates for one of the plutons. The intrusions are quartz-porphyr granodiorites, and plutons intrude yet are not offset by N-S trending, west verging, thrusts thereby suggesting that they postdate compressional deformation. Mineralization occurs as skarns, as well as disseminated within the potassic zone of hydrothermal alteration. Mineralization includes both, botryoidal and massive hematite, and titanomagnetite is a common accessory mineral. De la Garza (1996) and González-Partida *et al*. (2003) proposed that NW-SE faults served as channelways for both stock emplacement and mineralizing fluid flow. According to Jones and Jackson (1999) mineralization in the district is structurally controlled and is syn-deformational in nature, most commonly in the form of tensional conjugate vein sets. González-Partida *et al*. (2003) also reported that hematite was trapped in late magmatic fluid inclusions.

Pyroclastic Oligocene age volcanic rocks overlie the intrusive suite and its host rocks. Six concordant zircons from the Nukay stock yield a weighted mean date of 63±2, and Levresse *et al*. (2004) interpreted the age to indicate the time of intrusion. ^{39}Ar-^{40}Ar data for biotites in iron rich skarn yields dates between 63 and 65 Ma (Jones and Jackson, 1999), suggesting rapid cooling, and/or intrusion at shallow crustal levels. The Paleocene age is in good agreement with previous proposals of a regional post-tectonic pulse of magmatism in the Sierra Madre del Sur (Morán-Zenteno *et al*., 1999). Plutons are characterized by adakitic signatures (Levresse *et al*., 2004), and Cerca-Martínez (2004) relate the production of adakites to a model of flat subduction that explains stress transfer across southern Mexico during the Laramide orogeny. Nonethe-

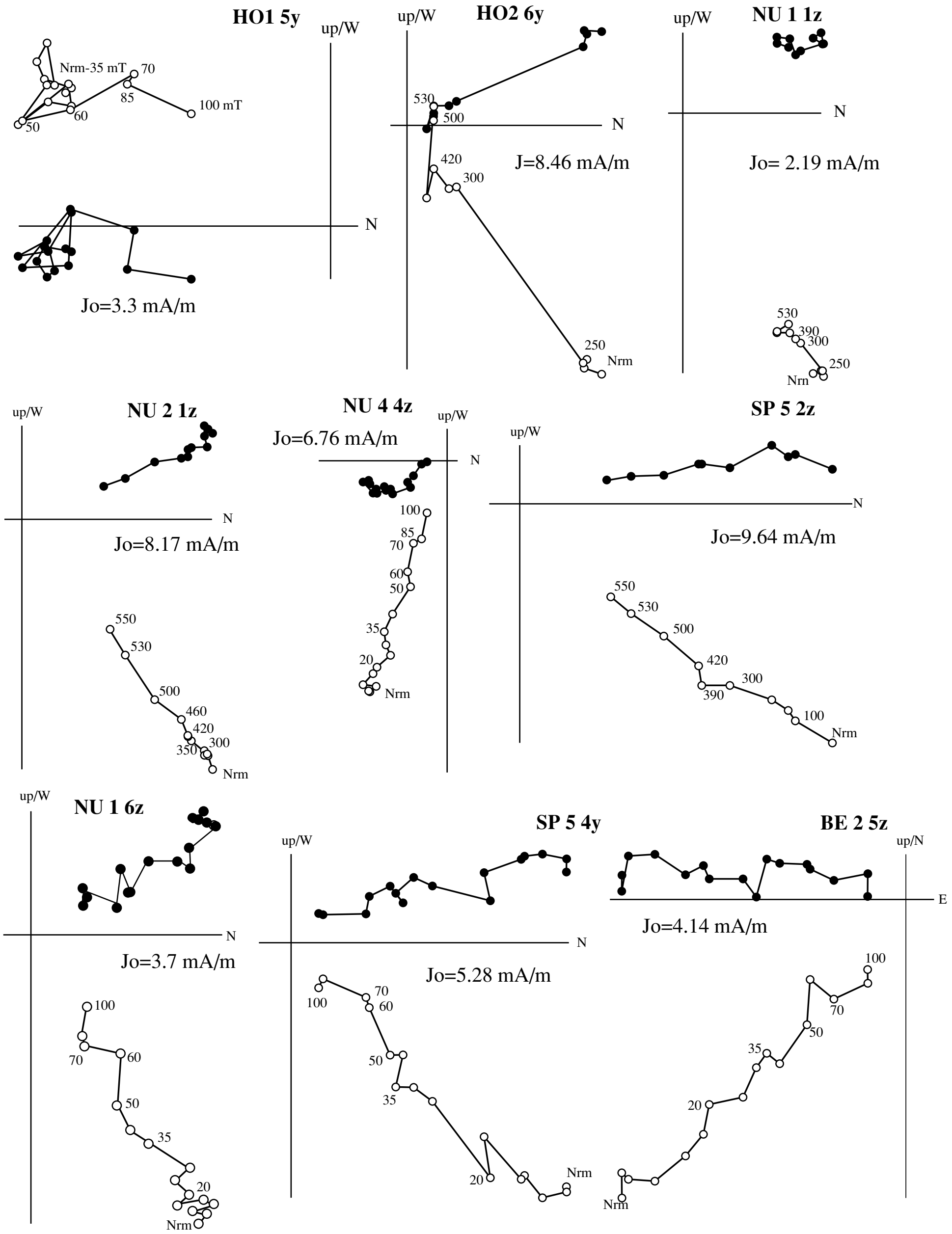

Fig. 3. Orthogonal demagnetization diagrams for selected samples of the Mezcala intrusive suite. Closed (open) symbols are projections on the horizontal (vertical) plane.

less, the plutons themselves could have experienced post-Laramide deformation, as associated alteration halos and mineral zonations are somewhat asymmetric with respect to the pluton shape. Skarn deposits are well developed vertically along the plutons contacts with the Morelos Formation, preferably at the WNW-ESE margins. The map of the district also shows northwest-trending lineaments of mines, and the cross section shows west-dipping bodies of massive iron oxides and jasper at the Bermejal mine (Levresse *et al.*, 2004).

The general structure of the Guerrero-Morelos platform, host to the Mezcala intrusive suite, is that of an anticlinorium bordered by, and structurally lower than, two thrust systems oriented north-south, with opposite vergence, to the east and west (Fig. 1). Both major and minor folds axes in the anticlinorium form a complex pattern. The general orientation of Laramide structures in the Morelos Formation are notably disturbed in the area north of the Balsas River, where the fold-axes are rotated counterclockwise forming a flower o fan structure. This feature is evident in air photographs and digital elevation models. Interpretations about the origin of this fan include a decollement in the subsurface (de Cserna *et al.*, 1980) or generalized anticlockwise rotation linked to strike-slip displacement (Molina-Garza *et al.*, 2003).

3. Sampling and Methods

We collected samples from 18 paleomagnetic sites from three intrusions of the Mezcala intrusive suite and their host rock (Fig. 2). Two sites were collected from the relatively small La Hormiga body, one of them in contact rocks including recrystallized limestone; seven sites were collected at the Nukay mine, five at San Pedro mine, one site was collected at the Bermejal mine, and three additional sites were collected from smaller, unmapped intrusions. Samples were drilled in the field using a gas-powered drill, and oriented in situ using magnetic and sun compasses and an inclinometer. Five to seven oriented samples were obtained at each site. In the laboratory, standard 2.1 cm high specimens were prepared for NRM (natural remanent magnetization) measurements. NRM was measured using a JR5 spinner magnetometer housed in a shielded room at the paleomagnetic laboratories of the Centro de Geociencias and Instituto de Geofísica. All samples were subjected to alternating field (AF) and thermal stepwise demagnetization using commercial equipment. Maximum available induction for AF demagnetization is 100 mT, and maximum temperatures used in thermal demagnetization were of 550°C. Samples were visibly altered and often destroyed during heating experiments, preventing us to reach higher temperatures.

The characteristic magnetization was interpreted from orthogonal demagnetization diagrams (Zijderveld, 1967). Directions were estimated using three-dimensional least square fits (Kirschvink, 1980). Site means and overall means were calculated assuming the directions are reasonably modeled by a Fisher distribution. Deformation of the plutons (tilt or tectonic rotation) was estimated comparing observed and expected directions. The latter were determined using a reference paleomagnetic pole for the North America craton located at 75.2°N–168.4°W (calculated from the paleomagnetic database of McElhinny and Lock, 1990). We also compared the results for the Mezcala pluton suite with observed directions in similar age rocks in southern Mexico.

4. Paleomagnetic Results

Magnetizations of the intrusions are relatively simple; NRM intensities are moderately high, and can be measured with good precision. Most of the samples have nearly univectorial magnetizations with linear trends to the origin, or linear decay to the origin after removal of a small north directed component interpreted as a viscous overprint (Fig. 3). Occasionally the overprint is more developed, and spurious magnetizations of low coercivity are also locally present. The characteristic magnetization (ChRM) is of relatively high coercivity, with median destructive fields between 35 and 50 mT and maximum coercivities over 100 mT. The ChRM is of high discrete laboratory unblocking temperature, greater than 550°C, but as mentioned above maximum unblocking temperatures could no be determined in most cases because samples were altered during thermal demagnetization experiments.

Isothermal remanence acquisition curves (IRM; Fig. 4) suggest the presence of a soft and a hard magnetic phase. Most of the samples are dominated by the soft phase, which is interpreted to be magnetite, but the presence of hematite is evident in data for recrystalized limestone form the intrusive contact. Hysteresis curves (Fig. 5) indicate that a mixture of multi-domain and pseudo-single domain grains characterizes the intrusions, with a more notable contribution from multi-domain grains in those sites that did not yield well defined magnetizations.

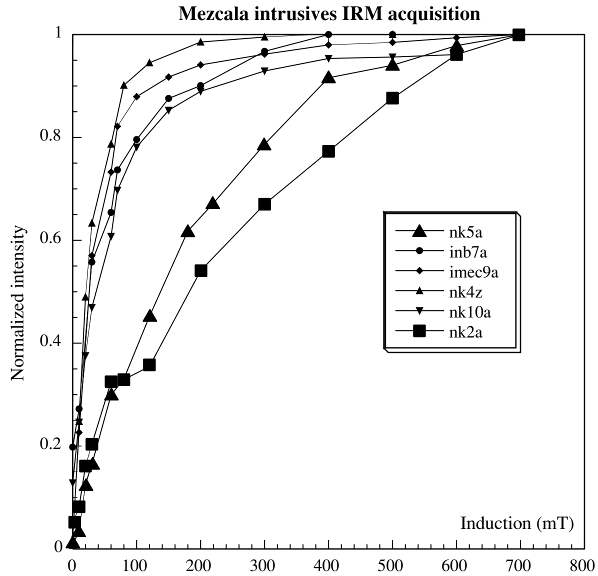

Fig. 4. Normalized IRM acquisition curves of selected samples.

The rock magnetic data, in combination with demagnetization behavior, suggest that the ChRM resides primarily in magnetite, but with small contributions of hematite in some of the samples. The ChRM is of northwest declination and positive inclination. Only site HO1 is of reverse polarity (southeast directed and of negative inclination). Site-means are based on reasonably well-grouped directions, with k values between about 28 and 240. Some of the means are defined by only four samples and α_{95} values range from 5.3° to 29.8°. Between-site dispersion is relatively high, and most noticeable is a girdle distribution of site means (Fig. 6). Four sites, all from a relatively small area southeast of the Nukay mine yield anomalously steep southwest-directed magnetizations. These site means are well defined in three of the sites, and demagnetization behavior of these samples is similar to that observed in other sites. Because the sites are relatively close, we infer that they may lie within a large block that has been displaced with respect to its original position either by slumping or by other means. These sites (nu4, n5, icc, and nki) were excluded from the grand mean. Three sites that failed to provide interpretable data in demagnetization experiments were excluded from final calculations. Also, two more sites (nk and imec) were excluded from the overall mean, as they did not yield acceptable statistics. The site mean distribution is somewhat streaked, with declinations varying between 280° and 350°, and inclination clustered between 30° and 45°. This distribution suggests that differential rotation between sites may have occurred. There is, however, no clear systematic geographic distribution of declinations; although sites from San Pedro mine appear to be slightly more discordant than other sites. We thus assert that the overall mean reflects the "average" deformation that affected the sampled area.

5. Data Summary

Although the number of accepted sites is relatively small, we assume that sampling is sufficient to average paleosec-

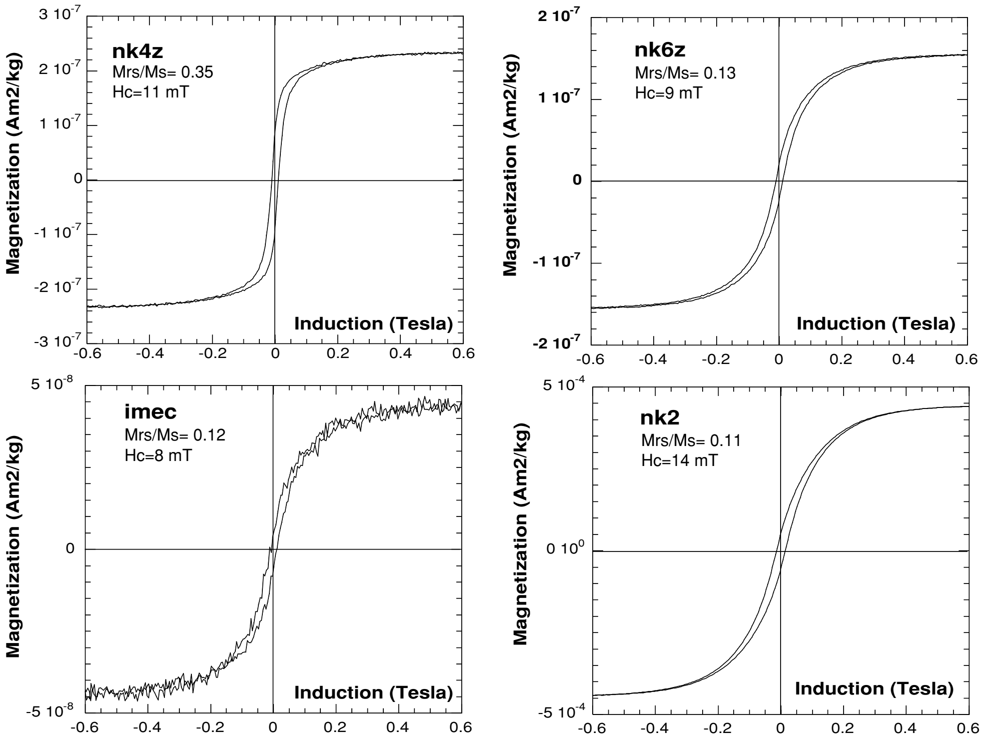

Fig. 5. Examples of hysteresis curves obtained for samples of the Mezcala intrusive suite.

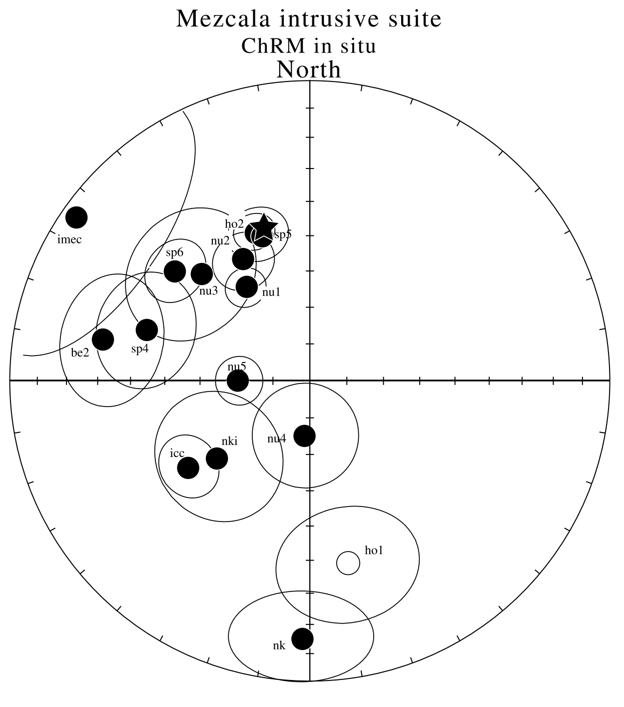

Fig. 6. Equal area projection of site means in in-situ coordinates. Closed (open) symbols are projections on the lower (upper) hemisphere. A star indicates the expected paleomagnetic direction.

Table 1. Paleomagnetic data for the Mezcala intrusive suite.

Site	N	dec	inc	k	α_{95}
be2	4	281.6	32.5	34.4	15.9
ho1	4	168.4	−36.8	28.4	17.5
ho2	5	340.5	46.9	97.8	7.8
nu1	4	325.4	59.0	288.6	5.4
nu2	5	330.9	52.3	90.0	8.1
nu3a	4	311.8	45.2	27.7	17.8
nu4*	4	184.7	75.0	42.3	14.3
nu5*	4	270.1	70.8	201.3	6.5
sp4	4	287.1	41.9	40.4	14.6
sp5	5	339.5	45.9	210.7	5.3
sp6	3	309.3	41.5	220.6	8.3
icc*	6	234.5	48.9	65.7	8.3
nk**	7	181.7	14.8	15.0	15.7
nki*	7	235.7	60.4	6.5	25.7
imec**	7	304.8	−5.3	5.1	29.8
Selec.	9	318.5	47.1	18.5	12.3

Here N is the number of samples used to calculate the mean; dec and inc are the mean declination and inclination and k and α_{95} are the parameters of the Fisher statistics. Sitess with poor statistics (**), and sites with steep Inclinations (*) were excluded.

ular variation. Our argument is based on the observation of at least one-site recording reverse polarity magnetizations and the interpreted time-span of intrusion emplacement and cooling based on U-Pb and Ar-Ar geochronological data. The sites with anomalously steep directions were excluded from the calculation of an overall mean. The overall mean was calculated using both Fisher and Bingham statistics, because the latter are more appropriate to non-symmetric distributions of site means.

Site mean directions are plotted in Fig. 6; paleomagnetic data and statistical parameters are listed in Table 1. The overall mean is of Dec=318.5, and Inc=47.1 (n=9 sites; k=18.5, α_{95}=12.3°; statistics are listed in Table 1). The overall mean direction is discordant with respect to the North America reference direction (Fig. 6) in both declination (more westerly) and inclination (steeper). The compar-

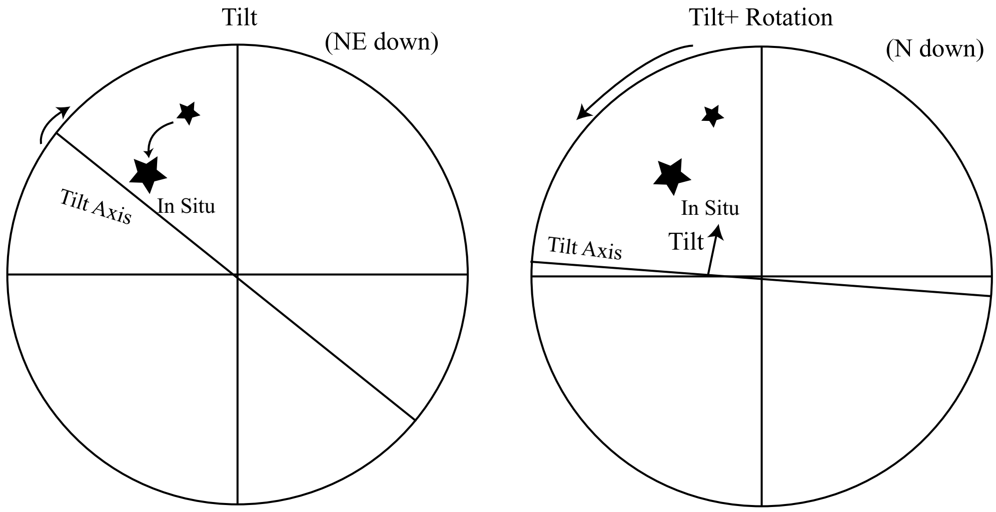

Fig. 7. Schematic model to describe the deformation history (tilt and/or rotation) inferred for the region of Mezcala.

ison of expected and observed directions indicates a rotation of 26°±15° and a flattening value of 16°±16°.

6. Discussion

The observation of anomalies in both declination and inclination can be best explained by about 40° of tilt down-to-the-northeast about a NW trending axis. The streaked distribution of site means is perpendicular to a NW trend. The interpretation is not unique, and the discordant grand mean direction may also be explained by a combination of a smaller amount of tilt and counterclockwise rotation, as discussed below. Although the intrusions lack paleohorizontal indicators, we note that cross-sections of the mine show west-dipping bodies of massive iron oxides and jasper that one can assume to have an attitude closer to vertical.

Because there is independent evidence for tilt of the plutons, and because previously published paleomagnetic data for southern Mexico rule out latitudinal displacement of this region with respect to North America, we are confident that paleomagnetic data for the Mezcala intrusive suite indicate some magnitude of tilt. Although the paleomagnetic directions can be restored with a simple tilt of 40° about a NW-SE axis, a combination of a smaller amount of tilt and about 20° of rotation about a vertical axis seems to be a more likely way to explain the discordant directions. These two models to restore the discordant directions are shown in Fig. 7.

Recently, Molina-Garza *et al.* (2003) reported paleomagnetic data for the Cretaceous marine sequence (Morelos and Mezcala formations) in the western region of the Guerrero-Morelos platform, in localities along Zopilote canyon about 20 km south of the study area. These authors interpreted the ChRM of the Cretaceous marine sequence as a synfolding magnetization, thus contemporaneous with the Late Cretaceous Laramide deformation. The mean direction observed in the Morelos and Mezcala formations (D=323.1°, I=36.6°) was interpreted to indicate about 19° of counterclockwise rotation of the sampling area. Given the relatively short distance between Zopilote canyon and the Mezcala mining district and the apparent structural continuity between these localities (Cerca-Martínez, 2004), it is likely that at least part of the deformation that affected the Cretaceous marine sequence affected the intrusive suite as well. For instance, a rotation of 20° about a vertical axis and tilt of 15° about a NW-SE trending axis can also restore the discordant directions observed in the Mezcala district (Fig. 7).

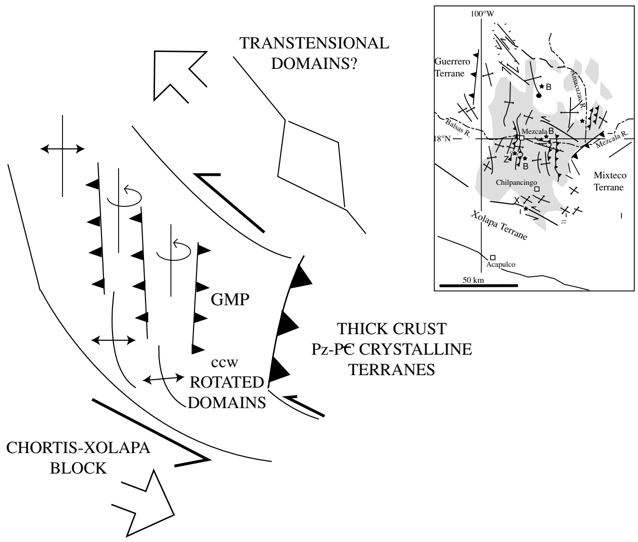

Fig. 8. Idealized model for the mid-Tertiary deformation of the Guerrero-Morelos platform region. See text for further explanation.

Molina-Garza *et al.* (2003) also noted that small to moderate counterclockwise rotation has been paleomagnetically recorded by Cretaceous to Paleogene rocks in nearly all localities studied in southern Mexico in the Guerrero and Xolapa terranes, east of and within the Guerrero-Morelos platform (Fig. 8). Inferred rotations average about 15°. In a recent study, Molina-Garza and Ortega-Rivera (2006), demonstrated that upper Eocene strata of the Balsas Formation at two localities in the Guerrero-Morelos plataform record small (-9°±8°) to statistically insignificant (+1.2°±8°) rotation. The Tierra Caliente intrusion (Xaltianguis) of early Oligocene age is the youngest unit in the region that records rotation ($-15°\pm23°$, counterclockwise), but the result is of relatively low reliability based on a small number of sites (Urrutia-Fucugauchi and Molina-Garza, 1995). A study of the Balsas Formation in a locality north of Taxco (Urrutia-Fucugauchi, 1983; Fig. 1) reports a relatively large rotation in these rocks ($18°\pm19°$), but again the result is of relatively low reliability as it is also based on a small number of samples. Although more reliable data are needed from upper Tertiary rocks in southern Mexico, we would argue that most rotations had ceased by Oligocene time, after deposition of the Balsas Formation, as indicated by the more reliable data for these rocks at localities on the Guerrero-Morelos platform (Molina-Garza and Ortega-Rivera, 2006). This, in turn, would imply that the driving mechanism of the counterclockwise rotation operated from latest Cretaceous to early Oligocene time.

The results for the Mezcala intrusive suite are consistent with the notion that Laramide structures of the Guerrero-Morelos platform were reactivated by younger deformation, which involves lateral slip along structures parallel to present Pacific margin of southern mexico such as the Tierra Colorada shear zone. The contrasting orientation of NW-SE trending structures within the Mezcala mining district that offset the plutons and N-S trending Laramide structures, suggests that the discordant paleomagnetic directions are best explained by a combination of tilt and rotation. Because the tilt proposed for the Mezcala intrusive suite is consistent with reactivation of the Laramide structures, the observation of tilt and rotation is also consistent with a transpressional setting, as previously proposed by Cerca-Martínez *et al.* (2004). Figure 8 shows a model that explains systematic rotation about vertical axes in rocks of the Guerrero-Morelos platform.

The model proposed here implies that the area has been under the influence of a left-lateral shear couple, and that north trending Laramide thrust faults acted as free surfaces that may have accommodated rotation of independent blocks. Rotation would thus be linked to transpression, as has been proposed for this region by Cerca-Martínez (2004). Modest rotation may be accommodated by horizontal slip along strike on the thrust faults or by different degrees of shortening along strike in the thrust faults. Additional rotation may have occurred by fault-drag near the major shear zones (e.g., south of Chilpancingo; Fig. 1).

The subsurface structure of the Guerrero-Morelos platform is unkown, but lateral facies and thickness changes have been proposed (Hernández *et al.*, 1997). Thickness variations of Cretaceous platform rocks and the presence (or absence) of lubricated intervals such as evaporates are likely to have influenced rotation, but to what degree it is presently unknown. We note that both the Zopilote canyon sites and the Mezcala sites, are in the region where the platform gradually deepens to the west, but the effects of the platform structure on the rotation can only be determined with accurate palinspastic reconstructions and more detailed study of facies thickness variations.

7. Conclusions

Rocks of the Mezcala intrusive suite yield somewhat dispersed and discordant paleomagnetic directions. The magnetizations are reasonably well-defined and reside primarily in magnetite. These discordant magnetizations are interpreted in terms of modest tilt and vertical-axes rotations. Overall, rocks of the region of the Guerrero-Morelos platform, in southern Mexico, record counterclockwise rotation about a vertical axes. A model that explains those rotations invokes transpression during the Cenozoic.

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