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Early development and research in Paleomagnetism and Rock Magnetism in Mexico – "El Pozo" Laboratory of Paleomagnetism and Nuclear Geophysics

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Abstract. The first paleomagnetic laboratory in Mexico was established in the early 1970s, at a time when the foundations of plate tectonics were being developed and research on paleomagnetism and rock magnetism was expanding with new instrumentation and applications on a wide spectrum of the Earth's sciences. Paleomagnetic studies had provided quantitative evidence in support of the continental drift hypothesis and allowed estimation of paleolatitudes and tectonic displacements. Confirmation of polarity reversals and development of the geomagnetic polarity time scale provided the framework for interpreting the marine magnetic anomalies and estimation of sea floor spreading rates, age of ocean floors and plate motions. Rock magnetic studies expanded and opened new research frontiers on a range of natural and synthetic materials. Investigations on the spatial and temporal variations of the geomagnetic field provided the basis for applications in tectonics and stratigraphy at a range of scales. The creation of the laboratory in Mexico involved collaboration with paleomagnetic laboratories in other countries, particularly with Buenos Aires, Argentina, Newcastle, UK and Sao Paulo, Brazil, which has continued and expanded over the years. From the start, research themes covered a wide spectrum with multidisciplinary approaches ranging from paleomagnetic studies applied to plate tectonics, stratigraphy, paleosecular variation, paleointensities, modeling of marine and on land magnetic anomalies, archaeomagnetism and biomagnetism. Arising from practical needs, research also involved designing and construction of instruments and developing methods for rock magnetic and magnetic fabrics studies, and multidisciplinary projects on geochemistry, petrography, isotope geochronology and exploration geophysics.

Keywords: Paleomagnetism, paleomagnetic research, paleomagnetic laboratories.

Resumen. El Laboratorio de Paleomagnetismo en México se establece a inicios de los 70´s, en la época en que la teoría de Tectónica de Placas estaba siendo desarrollada y los estudios sobre paleomagnetismo y magnetismo de rocas se incrementaron con la introducción de nuevas aplicaciones e instrumentación. Los datos paleomagnéticos proveyeron la evidencia cuantitativa en apoyo de la hipótesis de Deriva Continental y permitieron la determinación de desplazamientos tectónicos y paleoreconstrucciones. La confirmación



de la ocurrencia de cambios de polaridad y la escala de polaridades magnéticas abrieron la posibilidad de interpretar los patrones de anomalías magnéticas marinas, estimar los cocientes de esparcimiento, la edad de la litosfera oceánica y los movimientos de placas. Los estudios de magnetismo de rocas se ampliaron y nuevas líneas de investigación en materiales sintéticos y naturales se desarrollaron. Los estudios sobre las variaciones espacio-temporales del campo geomagnético establecieron las bases para las aplicaciones en tectónica y estratigrafía. La creación del Laboratorio en México involucró la colaboración con los laboratorios de Buenos Aires, Argentina, Newcastle upon Tyne, Reino Unido y Sao Paulo, Brasil. Desde un inicio, las líneas de investigación abarcaron un rango amplio de temas, con un carácter multidisciplinario que cubrió estudios de tectónica de placas, estratigrafía, geomagnetismo, modelado de anomalías magnéticas, arqueomagnetismo y biomagnetismo. Los trabajos iniciales incluyeron el diseño y construcción de equipos y desarrollo de métodos para magnetismo de rocas y fábrica magnética, así como estudios complementarios sobre geoquímica, geocronología, isótopos y exploración geofísica.

Palabras Clave: Paleomagnetismo, investigación paleomagnética, laboratorios paleomagnéticos

1. Introduction

Paleomagnetic studies in the 1950's and 1960's documented that the amount of angular divergence of paleomagnetic directions from present-day geomagnetic directions appeared to increase with age of the rock units (Irving, 1964; McElhinny, 1973). Use of the statistical methods developed by Fisher and others permitted quantitative analysis of the paleomagnetic data. Paleomagnetic pole positions determined from directions assuming dipolar field configuration were distributed around the geographic pole for late Quaternary rock units. In contrast, paleomagnetic pole positions determined for older rock units were distributed farther apart, following an apparent path away from the geographic pole. These paths apparently displayed progressions of paleomagnetic poles which diverged for the different continents. These observations by paleomagnetists S.K. Runcorn, K.M. Creer, E. Irving and others provided the framework for analyses of polar wander and continental drift, providing quantitative evidence in support of large horizontal displacements of land masses in the geological past. The studies developed the basis for paleomagnetic applications in tectonics, defining the geocentric axial dipole, apparent polar wander paths (APWP) and paleosecular variation (PSV). Documentation of polarity reversals and epochs of constant polarity, which built on early observations in the nineteen and early twenty centuries, provided a stratigraphic framework for time varying geomagnetic field. Paleomagnetic and K/Ar dating studies of volcanic sequences in the western United States and islands of the western Pacific Ocean by A. Cox, B. Dalrymple, D. H. Tarling, R. Doell and I. McDougall permitted development of the geomagnetic polarity time scale.

The success of paleomagnetism in tackling large scale problems prompted studies of a wide range of formations of different ages in far apart localities and the establishment of paleomagnetic laboratories in several countries. Paleomagnetic studies were applied to geological and geophysical problems, such as the evolution of the supercontinent assemblages of Pangea, Laurasia and Gondwana, formation of the Atlantic and Pacific oceans, mountain building and stratigraphic correlations (Irving, 1964; McElhinny, 1973; Valencio et al., 1975 a, b; Tarling, 1983). In the following decades, paleomagnetic laboratories were being created in



South America, particularly in Buenos Aires, Argentina, Sao Paulo, Brazil and Mexico City, Mexico. In this note, we comment on the early development of paleomagnetism and rock magnetism in Mexico and the establishment of the Laboratory of Paleomagnetism and Nuclear Geophysics at the National University of Mexico in Mexico City.

2. Earth's sciences in the 1960's and 1970's

In the 1960's and early 1970's geophysical and geological studies developed the foundations of plate tectonics (e.g., Hess, 1962; Wilson, 1963, 1965, 1966; Vine & Matthews, 1963; Vine & Wilson, 1965; McKenzie & Parker, 1967; Ewing & Ewing, 1967; Isacks et al., 1968; Morgan, 1968; LePichon, 1968). The studies built on a wealth of data from marine geophysical surveys and early research on continental drift, paleomagnetism, structural geology and tectonics (Benioff, 1954; Runcorn, 1956; Irving, 1964; Bullard et al., 1965). The studies leading to plate tectonics had an integrative approach, resulting in novel syntheses of geological and geophysical observations and models. A central component in the development of plate tectonics came from the marine magnetic surveys and their interpretation in terms of sea floor spreading and geomagnetic studies of young volcanic sequences and radiometric dating using the K/Ar method (Cox et al., 1964; McDougall & Tarling, 1963). These studies lead to development of a geomagnetic time scale documenting polarity reversals and polarity epochs for the past ~3-4 Ma. These results were taken as a basis for interpreting long reversal sequences identified in marine magnetic anomaly profiles from different ocean basins (Heirtzler et al., 1968). The study represented a bold extrapolation of data and models which, when confirmed by further studies, provided strong support for sea floor spreading and plate tectonics, (McElhinny, 1973; Cox, 1973).

In the 1970's, Earth sciences were full of excitement as the new paradigms emerged and gained acceptance as further evidences on sea floor spreading, plate motion, subduction, transform faulting, mantle convection, and island arcs were being uncovered. Earth sciences were being transformed into a global enterprise with new studies and data coming from all ocean basins and remote parts of the continents. Closer home, studies were being carried out on the nature and evolution of e.g. the North America and Pacific plates, Pacific oceanic fracture zones, San Andreas plate transform boundary, Gulf of California, volcanic arcs and the smaller oceanic plates with the Juan de Fuca, Rivera, Cocos and Nazca (e.g., Menard, 1966; Atwater, 1970; Molnar and Sykes, 1969).

In this context, for an undergraduate student in an institution far removed from the ongoing research having an opportunity of participating in the 1973 East Pacific Rise Experiment was an unexpected gift. The marine geophysical surveys were made along the Pacific, Rivera and Cocos plates, involving acquisition of seismic, bathymetric, gravity and magnetic data. Being able to interpret bathymetric data over the rise at the intersection of a major oceanic fracture zone and marine magnetic profiles with their polarity reversal sequences was a great experience to enter into plate tectonics for an undergraduate student (Urrutia Fucugauchi et al., 1974; Del Castillo & Urrutia Fucugauchi, 1975). This was followed by the 1974 Gulf of California marine survey as part of the Deep Sea Drilling Project (DSDP), involving geophysical studies of the East Pacific rise and Tamayo and Rivera fracture zones. The studies on the East Pacific rise and Cocos plates allowed interpretation of the subduction zone-volcanic arc in southern Mexico, which was being interpreted in the context of plate tectonics (e.g., Molnar and Sykes, 1969). The tectonic model for the continental volcanic arc involved changes



in the subduction parameters of the Cocos and Rivera plates beneath the Pacific margin (Urrutia Fucugauchi and Del Castillo, 1977). Analyses of the spatial-temporal patterns of volcanic activity in the Sierra Madre Occidental resulted in a tectonic model in terms of changes in subduction convergence and angle in response to plate interactions along the western North American margin (Urrutia Fucugauchi, 1978a). Learning on how paleomagnetic studies quantified continental drift making continental paleoreconstructions possible and on geomagnetic polarity reversals providing detailed stratigraphy, which together allowed measuring sea floor spreading rates, plate motion and dating of the ocean crust certainly aided to make choices on research subjects for postgraduate studies and a professional career.

No mention of plate tectonics and marine geophysical studies was made in undergraduate curricula, and it will take several years before the new concepts were incorporated by the professional and academic Mexican community. Continental drift, mountain building, origin of oceanic crust and Earth's interior structure were presented in terms of the fixist hypotheses of vertical tectonics and geosynclinal evolution. Some subjects like continental drift were even addressed as discarded ideas in a historical context. Relatively few studies incorporated the new tectonic models and concepts (e.g. see De Cserna, 1969, 1971). In this context with no exposure to the new developments in plate tectonics, my thesis projects represented an interesting challenge, involving marine magnetic anomaly studies on the East Pacific rise and Cocos plate and paleomagnetic studies, magnetic polarity stratigraphy and tectonics.

3. Paleomagnetic Laboratory

At the time a major limitation was the lack of laboratory facilities for geophysical research. There were relatively few groups in geosciences and certainly no paleomagnetic laboratories in the country; therefore a major effort in constructing basic laboratory facilities was implemented. Paleomagnetic instrumentation and methods had been developing at several laboratories, which included some of the pioneering groups in Newcastle and Cambridge, UK, Paris, France, Utrecht Netherlands and Tokyo, Japan (Collinson et al., 1967). The type of instruments used for magnetic measurements and stability and vectorial composition analyses of remanent magnetizations required magnetic-free spaces and low electromagnetic interference. Laboratories were installed at special facilities far from urban environment and built in wooden buildings, like the "Close House" laboratory at Newcastle upon Tyne or those of Munich and Utrecht Universities.

At the National University of Mexico, laboratory facilities were installed in a building, which had underground spaces some <30 m below ground level and nick named as "El Pozo" (Fig. 1). In the early stages, collaboration with D. A. Valencio and J. F. Vilas were important in designing and implementing the analytical facilities. The Paleomagnetic Laboratory in the University of Buenos Aires was well equipped, and included several instruments designed and constructed by the group. In the 1970's Valencio, Vilas and a growing group of talented researchers were involved on a wide range of projects, including those related to continental paleoreconstructions and evolution of the Pangea and Gondwana supercontinents (e.g., Vilas, 1974; Valencio et al., 1975a,b; Rapalini et al., 1989). Other projects related to magnetic polarity stratigraphy and paleosecular variation in continental sedimentary sequences like the Paganzo Group (Valencio et al., 1977). Collaboration between the Buenos Aires laboratory and UNAM expanded through a



series of workshops and meetings with the Paleomagnetic Laboratory at the University of Sao Paulo, Brazil. The Sao Paulo laboratory was involved in different projects related to tectonics, stratigraphy, etc, including studies in the Parana flood basalt province, the Brazilian shield and the Gondwana assembly. These studies continued and expanded over the years (e.g., Ernesto et al., 1990). The collaboration network later in the early 1980's rapidly expanded to include the Geomagnetic Observatories and the laboratories and groups being developed in other countries in the region, including Venezuela, Peru, Colombia, Chile and Uruguay, becoming the Latinamerican Group of Paleomagnetism.

The number of groups and researchers in Earth sciences in the region was small, and laboratory and geophysical observatory facilities were limited to a few countries and places. One of the major concerns of the group was then directed to educational and training programs, and to promote and facilitate collaboration among the groups (e.g., Valencio and Schneider, 1985; Urrutia Fucugauchi, 1982c; Lomnitz, 1982). International collaboration with research groups from other nations, which had already being established earlier, was also looked for and expanded. Fruitful collaboration projects were developed, among other colleagues, with K. Creer, D.H. Tarling, W. MacDonald, E. Irving, A. Cox, M. McElhinny and B. Embleton.

The laboratory facility at UNAM was built inside a thick basaltic lava sequence of a historical 2 ka old eruption, and offered special conditions for trace element and isotope geochemistry with low radioactivity



Laboratory of Paleomagnetism "El Pozo"

National University of Mexico



Figure 1. Partial views of the Paleomagnetic Laboratory El Pozo at the National University of Mexico UNAM and a composite Landsat image of Mexico.



backgrounds. The building was however located far from other buildings in the campus, and electromagnetic noise appeared relatively low. Measurements with proton and fluxgate magnetometers located low gradient zones and use of Helmoltz coils and mu-metal shielding provided adequate operational conditions.

Concerning the instrumentation, efforts involved implementing a three-axis fluxgate laboratory magnetometer to measure magnetizations of large block samples, acquiring a spinner magnetometer from Princeton Applied Research, designing and constructing an alternating field (AF) demagnetizer and tools for collecting and preparing rock specimens in the field and laboratory. The layout for the three-axis fluxgate was similar to the astatic magnetometers and worked well with strongly magnetized volcanic rocks and bricks. The AF demagnetizer was built with sets of coils for applied fields within shielding Hemholtz coils and permitted treatment of specimens using the static and rotational methods with maximum fields up to 100 mT. Efforts also included developing and implementing the methods for analysis of rock magnetic, intensity and directional data, remanence stability and statistical tools based on Fisher statistics and vector analysis.

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4. Tectonics

Initial projects of the paleomagnetic laboratory included analyses of the Pangea supercontinent assembly, and subsequent break up and drift apart of North and South America, with formation of the Gulf of Mexico and Caribbean Sea (e.g., Fig. 2). Paleomagnetic studies were carried out in the Precambrian and Paleozoic formations in southern and northern Mexico, aimed to investigate the tectonic evolution of the area and its relation to Pangea evolution (Van der Voo, 1979, 1981; Urrutia Fucugauchi, 1984). The studies represented major challenges, because of the complex multivectorial magnetizations, lack of radiometric dates and as yet incomplete geological mapping (Urrutia Fucugauchi, 1984). Paleomagnetic studies documented large tectonic rotations and relative paleopositions of the Precambrian Oaxaca complex in the Pangea assembly (Ballard et al., 1989) (e.g., Fig. 3), and evolution of the southern Mexico terranes during Paleozoic and Mesozoic times (Urrutia Fucugauchi & Van der Voo, 1983; McCabe et al., 1988). In parallel, studies were initiated in the sequences of the volcanic arcs in the Trans-Mexican volcanic belt (TMVB) and Sierra Madre Occidental. Paleomagnetic data for TMVB volcanic units revealed rotated paleomagnetic directions, suggesting occurrence of counter-clockwise block rotations associated with oblique plate convergence at the Middle American trench and back arc deformation (Urrutia Fucugauchi & Pal, 1977). Studies also documented tectonic deformation in northern Mexico, related to regional tectonics of the Basin and Range and regional transcurrent faulting in southern United States and northern Mexico





Figure 2. Schematic maps of the Mexico, Central America and Caribbean region, showing the plate boundaries and major tectonic features. The inset map shows the trajectories for the drift apart of North and South America following Pangea break up.

(Urrutia Fucugauchi, 1981a). The paleomagnetic data showed discordant paleomagnetic directions for Early Tertiary volcanic rocks in northern Mexico, which were interpreted in terms of counterclockwise regional rotations (e.g., Fig. 4). Studies involved multidisciplinary approaches with paleomagnetism, geochronology and geochemistry (Pal & Urrutia Fucugauchi, 1977).

A preliminary APWP for Mexico documented a path that correlated with the corresponding APWP for cratonic North America (Urrutia Fucugauchi, 1979a) (Fig. 5). Paleomagnetic poles from sites at the western North American margin diverged from the reference APWP, indicating clockwise rotation of terranes along the margin (McWilliams, 1983). In Mexico, discordant paleomagnetic poles were also documented but with different patterns characterized by counter-clockwise rotations (Urrutia Fucugauchi and Pal, 1977; Urrutia Fucugauchi, 1981b, 1984).

Tectonostratigraphic terrane analyses showed that the western margin of North America is formed by several allochtonous terranes, accreted to North America during the Mesozoic and Cenozoic (May et al., 1983, McWilliams, 1983). Paleomagnetic studies of some of the terranes indicated large latitudinal displacements, with paleopositions farther south. Paleoreconstructions indicated past positions in the Mexico region. Accretion of terranes and oceanic plateaus were related to regional deformation during the Laramide orogenesis.

Paleomagnetic studies documented tectonic rotations and provided quantitative data for paleoreconstructions. Recognition on the differences in basement and stratigraphy allowed characterization



Late Precambrian APWP and Relative Paleopositions of Oaxaquia



Figure 3. Example of paleomagnetic results for the Grenvillian Oaxaca Complex in southern Mexico (Ballard et al., 1989). The Oaxaca complex is interpreted as part of a larger tectonic element named Oaxaquia (see map). Figures above show the apparent polar wander paths and two distinct alternative relative positions for Oaxaquia (darker zones), close to the Canadian Grenvillian province and northern Africa and South America.

of blocks or terranes with contrasted tectonic evolution, which resulted in the tectonostratigraphic analysis. Paleomagnetic studies at the time were also being carried out by other groups, which had become interested in the tectonics and stratigraphy of Mexico (e.g., Watkins et al., 1971; Cohen et al., 1981; Gose & Sanchez Barreda, 1981; Bobier and Robin, 1983; Kleist et al., 1984). Attempts at tectono-stratigraphic synthesis involved a series of special volumes on the paleomagnetism and tectonics of the Middle America region as part of the International Lithosphere Program (e.g., Urrutia Fucugauchi, 1981c).

Tectonic syntheses for the origin and evolution of the Gulf of Mexico and the Caribbean in terms of the break up and drift of North and South America showed that the geological features were difficult to incorporate into plate tectonic models referred to magnetic anomalies in the central Atlantic Ocean e.g., Emery & Uchupi, 1984; Ladd and Buffler, 1985). Earlier synthesis of paleomagnetic data were aimed at unraveling the regional tectonics of the Mexico, Central America and the Caribbean (e.g., Fig. 6). Paleomagnetic data documented the occurrence of vertical axis rotations of various tectonic elements in the region, related to the relative plate tectonic motion of the major continental blocks and the Caribbean island arc of the Antilles.





Figure 4. Example of paleoreconstructions and tectonic model for northern Mexico derived from paleomagnetic data (see Urrutia Fucugauchi, 1981a). The tectonic model proposes a regional rotation of northern Mexico, to account for the apparent displacement between Nevada and Mexico in the Mesozoic-Cenozoic orogenic belt of western North America along the Texas lineament zone.

5. Geochemistry and Geochronology

The formal name adopted in 1974 was Laboratory of Paleomagnetism and Nuclear Geophysics, which referred to the analytical facilities for major oxides and trace element geochemistry, including nuclear activation analysis (NAA) and natural radioactivity. Thus, the laboratory had instrumentation for working with radioactive materials such as gamma ray spectrometers and scintillometers. Some of the first samples analyzed by NAA included dredged tholeiitic basalts from the Gulf of California cruise and volcanic rocks from the paleomagnetic surveys in the TMVB, which gave the first rare earth element (REE) data (Pal and Urrutia-Fucugauchi, 1977; Lopez et al., 1978; Urrutia Fucugauchi, 1979b, 1982a). The geochemistry laboratory involved generating reference standard samples, as well as use of international standards (Perez et al., 1979). Recognizing that lack of facilities for geochronology was a limitation in paleomagnetic studies in tectonics and



stratigraphy, plans included collaboration projects involving K/Ar and radiocarbon dating, and construction of a geochronology and isotope laboratory. Collaboration started with the Instituto de Geocronologia y Geologia Isotopica (INGEIS) in Buenos Aires, with E. Linares, in combination with paleomagnetic projects. Paleomagnetic and K/Ar dating studies were carried out in the Cretaceous and Cenozoic volcanic sequences in the TMVB and in central-southern Mexico (e.g., Urrutia-Fucugauchi, 1980a; Linares and Urrutia-Fucugauchi, 1981). Results permitted investigations on geological mapping, volcanic stratigraphy and hydrothermal and metamorphism of the igneous units (De Cserna and Fries, 1981).

Analyses of geochronological data from the Sierra Madre Occidental, which constitutes a continental volcanic arc developed associated with plate subduction along the western North America margin during the late Mesozoic and Paleogene times, permitted to reconstruct the evolution of the subduction system and plate interactions along the margin, with spatial-temporal patterns of arc magmatism associated with changes in subduction parameters (Urrutia Fucugauchi, 1978a).

6. Rock Magnetism and Magnetic Anisotropy

A considerable part of the early efforts was directed to rock magnetism and magnetic fabrics studies. Rock magnetic investigations, initially focused on understanding magnetization acquisition mechanisms and



Apparent Polar Wander Path (APWP) for Mexico

Figure 5. Summary of paleomagnetic data for the Mesozoic and Cenozoic, and the preliminary 1978 apparent polar wander path for Mexico (see Urrutia Fucugauchi, 1979a).





Paleomagnetic Data for Mexico and Central America Region

Figure 6. Compilation of paleomagnetic data for different regions in Mexico, Central America, Caribbean and northern South America. The schematic map shows the observed (red arrows) and expected (blue arrows) paleomagnetic directions reported in different studies.

providing information on the paleomagnetic record, were expanding with new instrumentation and analytical methods. This was opening new research fields, including studies on synthetic materials and detailed analysis of domain states, etc (e.g., Shive, 1983; Harstra, 1983). Rock magnetic experiments were conducted on a variety of materials, and included developments of approaches to characterize the magnetic mineralogy, magnetic carriers and domain states in volcanic, sedimentary and metamorphic rocks (Urrutia-Fucugauchi, 1980b,c,d, 1981a,b).

One of the projects was directed to measure magnetic viscosity and relaxation on red beds, granites and volcanic rocks (e.g., Urrutia Fucugauchi, 1981a). Acquisition of secondary magnetizations, such as viscous remanent magnetization (VRM) is part of the remagnetization processes modifying the paleomagnetic record. For paleomagnetic studies, considerable effort is expended in identifying and removing secondary magnetizations. One of the developments was an experimental method to measure magnetic viscosity and relaxation times in short time scales in the order of 100-1000 seconds, representing superparamagnetic behavior at room temperature (Fig. 7). The short term viscous build up observed in the experiments on different lithologies has implications for secondary magnetizations acquired in the laboratory, and is in the order of remanent magnetization measurement scales.

Magnetic characterization of magnetic mineralogy and domain state involved measurements of hysteresis loops at room and liquid nitrogen temperatures and variation of magnetic susceptibility. One of the interesting results from these studies showed variation patterns for intermediate composition



titanomagnetites characteristic of tholeiitic basalts occurring in continental basalts (Urrutia-Fucugauchi et al., 1984).

Studies on magnetic fabrics using the anisotropy of magnetic susceptibility (AMS) measured at low and high fields were undertaken in samples from different geologic and tectonic settings. Magnetic fabric studies were being applied to a wide range of geologic and geophysical problems (Hrouda, 1982), in particular to investigate deformation effects on different tectonic processes (e.g., Henry and Daly, 1983; Borradaile, 1988). Studies were carried out on continental sedimentary deposits, including red bed sequences of Middle Jurassic and Paleogene ages, which documented the paleogeography and depositional conditions. Results permitted to estimate paleocurrent directions, and distinguishing depositional environments related to high and low energy conditions, inundation plains, etc. Another interesting result related to observations on inverse fabrics, which constituted a first report on inverse fabrics in red beds. A model for development of inverse fabrics in red beds was proposed as part of the studies.

Other studies were directed to investigate composite fabrics using low and high field torque methods. Effects of laboratory heating employing stepwise temperature treatments were investigated on different lithologies. Results indicated that in the case of sedimentary units, heating resulted in fabric enhancement associated with alteration-induced magnetic phases that mimic the original fabrics (Urrutia Fucugauchi,



Figure 7. Examples of rock magnetic experiments on short term magnetic viscosity and relaxation. Data illustrated is for samples of red beds (see Urrutia Fucugauchi, 1981b).



1981b). Studies conducted in glacial tillite deposits from Islay and Garvellachs islands, Scotland (Urrutia Fucugauchi & Tarling, 1983) also gave results showing the potential of temperature treatment for separating and characterizing multi-component fabrics (Fig. 8).

AMS studies on volcanic rocks were used to investigate on emplacement modes and flow directions on a variety of settings. Studies were carried out on lava and pyroclastic flows associated with monogenetic and stratovolcanoes, which provided indications on different fabric lineation and foliation patterns arising from flow conditions. Volcanic units from the Los Azufres and Los Humeros calderas were also carried out, which permitted to study, in addition to the emplacement mode and flow characteristics, the effects of hydrothermal alterations.

A magnetic fabric study of a columnar basalt from Salto de San Anton permitted to investigate on the emplacement mode and formation of columnar jointing (Urrutia Fucugauchi, 1982b). The AMS results documented a nearly horizontal foliation plane, consistent with a magma flow pattern without effects of convection, indicative of thermal contractive stresses during column formation. AMS ellipsoids are dominantly prolate, suggesting magnetic particle elongation, possibly due to crystal growth or particle realignment normal to vertical stress field during thermal contraction. Apparent spatial variations on the column sides on bulk susceptibility, anisotropy degree and lineation patterns may reflect weathering effects or hydrothermal alteration.

7. Paleosecular Variation and Paleointensities

Most studies in the early stages were carried out on the volcanic sequences in the Basin of Mexico and the Trans-Mexican volcanic belt, using magnetic polarity stratigraphy. Studies on paleointensity methods using the Thellier method and methods based on anhysteretic remanence (ARM) were also carried out on Miocene and Quaternary volcanic rocks. Part of the work focused on development of reliability criteria for paleointensity determination (e.g., Urrutia Fucugauchi, 1978c, 1980a,b). Work on paleointensities have continued and significantly expanded in recent years. The studies have involved collaboration among the paleomagnetic groups in South America and with groups in other countries.

In a second stage, studies of paleosecular variation on lacustrine sediment sequences were also implemented, following paleomagnetic measurements of sediments in Tlapacoya archaeological site and the Chalco and Valsequillo basins. The paleosecular variation studies were combined with archaeomagnetic projects and directed to construction of a reference curve for dating and correlation. Studies on lacustrine sediments have evolved to include paleoclimatic and paleoenvironmental studies using magnetic susceptibility and magnetic properties as proxies in combination with other chemical, biological and physical proxies of climate and environment conditions, investigating Quaternary sediments from different lacustrine basins in central Mexico. Similarly, these studies have also significantly expanded in the past years, involving international collaboration.

8. Archaeometry an Archaeomagnetism

The project to build the underground transport Metro system in Mexico City in the early 1970's allowed geophysical surveys in the pre-Hispanic archaeological remains of downtown Mexico (Fig. 9).







Figure 8. Example of anisotropy of magnetic susceptibility data for tillite deposits from Scotland. Samples come from the Late Proterozoic Port Askaig Formation (Urrutia Fucugauchi & Tarling, 1983). Results reported correspond to an experiment on the effects of laboratory heating on the magnetic fabrics.

Geophysical surveys were undertaken during construction of the Metro line in the "Zocalo" Mexico City main square area next to the Cathedral and Presidential Palace (Del Castillo and Urrutia-Fucugauchi, 1974). The geophysical surveys included gravity, magnetics, electrical resistivity, seismic profiling and drilling, and aimed to locate several Aztec sculptures, including the "Piedra Pintada", an archaeological piece of the same dimensions as the Aztec Calendar, which was excavated and re-buried in Colonial times. Surveys uncovered several archaeological remains and basaltic sculptures (Figs. 9 and 10), but no signs of "Piedra Pintada". Results were important in defining new research projects in archaeometry and in archaeomagnetism. Early archaeomagnetic studies involved the volcano-sedimentary sequences in the Mexico and Puebla basins, including the Xitle lavas in Cuicuilco, Copilco and UNAM University campus, and the lacustrine sediments investigated in Chalco and Valsequillo (Urrutia Fucugauchi, 1975).

In the following years, geophysical studies of archaeological sites using different methods, including gravity, magnetic and seismic refraction have continued. In addition, archaeomagnetic studies on archaeological materials have been carried out (Urrutia Fucugauchi, 1975). Studies have been directed to construct a reference archaeomagnetic secular variation curve, for dating and correlation. Archaeointensity investigations have more recently incorporated, with construction of a reference paleointensity curve for the



past millennia for Mesoamerica. Construction of the reference curves is also partly based on results from studies in the young volcanic sequences in central and southern Mexico. Rock magnetic studies have been carried out on different materials including ceramics, clays and obsidians for provenance investigations. The rich archaeological heritage in the country that includes the development of the Olmec, Maya, Teotihuacan, Toltec, Mixtec, Zapotec and Aztec cultures offers ample opportunities for archeomagnetic studies.

Another project was related to investigating the knowledge acquired in the early Mesoamerican cultures on magnetism and geomagnetism. Historical information on ancient knowledge and construction of the first magnetic compasses shows that early records come from China, where the first magnetic compasses were constructed and use for orientation purposes. Records on the attractive properties of magnetite and loadstones come from Greece, with accounts on loadstones from the Magnesia region. Studies on some archaeological iron pieces recovered from archaeological sites indicated that the Olmecs may have noticed the orientation properties of iron oxides. In particular, reports on an elongated flat piece worked from iron



Colonial Downtown Mexico (XVI Century)



Figure 9. Example of archaeometry studies in the historical downtown district of Mexico City. The study area is located in between the Cathedral and the Zocalo main square area. The geophysical surveys were directed to search for Aztec archaeological sculptures and construction remains in the Great Temple are of Tenochtitlan (Del Castillo & Urrutia Fucugauchi, 1974).



ore seems to have been used as a magnetic compass. The level of knowledge about magnetism appears to have been enough to understand the orientation in the geomagnetic field. Additional evidence uncovered in the archaeological excavation projects comes from a head of a marine turtle made from a basaltic rock. The piece seems to have been carved to have the remanent magnetization vector pointing to the turtle nose, which can be simply observed by looking at the deflection of a magnetic compass as it is moved around the basalt piece.

In several Mesoamerican sites the orientation of urban and ceremonial centers, which are well traced and planned, shows an apparent systematic pattern. Most traces of the urban centers are oriented northsouth, which may reflect use of solar orientation. The high level of astronomical knowledge in ancient Mesoamerica is well documented, and it is possible that ceremonial centers were constructed with astronomical orientations, which is the case of several temples and pyramids. On the other hand, the urban centers show angular variations around the north-south axis up to 10-15 degrees, which will be unacceptable errors in the context of the high precession reached of astronomical observations. The angular dispersion range is however on the range of secular variation, suggesting that if magnetic orientation was being used for the urban designs, the orientations deviating a few degrees from geographic north may then reflect the secular variation at the sites.

9. Magnetics and Exploration Geophysics

Geophysical surveys were also part of the projects of the laboratory from the early stages, applied to studies of crustal structure, tectonics and mineral exploration (Urrutia-Fucugauchi and Delgado-Argote, 1976). The marine geophysical projects on the Cocos plate and in the mouth of the Gulf of California involved collection of magnetic anomaly data and modeling of magnetic anomalies (Urrutia-Fucugauchi et al., 1974; Del Castillo and Urrutia-Fucugauchi, 1975). Modeling involved calculation of the crustal response of lineated patterns with alternating normal and reverse polarity. The crustal models documented the age of the oceanic crust and the plate motion velocity and spreading direction in a segment of the East Pacific rise. The Cocos plate experiment also surveyed an area affected by transform faulting, which displaced the lineated magnetic anomaly patterns, and provided data on relative plate motion. The marine survey in the Gulf of California also involved collecting of dredged fragments of oceanic tholeiitic basalts, which were analyzed for major and trace element geochemistry and rock magnetic properties (Urrutia-Fucugauchi, 1979b, 1982a).

Projects linked to paleomagnetic and rock magnetic studies involved ground magnetics and aeromagnetics. Modeling of magnetic anomalies, especially over volcanic terranes, required estimation of magnetic properties and remanent magnetizations. Mineral exploration projects, in particular those related to iron ore deposits, benefit from joint investigations with paleomagnetic studies and geophysical surveys. Strongly magnetized units in particular need to take into account the induced and remanent components (Urrutia-Fucugauchi, 1977).

Mineral exploration projects also involved magnetic and paleomagnetism, with applied studies in iron ore and lead-zinc-iron sulphide deposits in southern and northern Mexico. Early studies were related to investigations on mineralization processes, e.g., studies in the Santa Eulalia sulphide mine in Chihuahua,



northern Mexico, and to survey the mineralized zones and location of iron ore bodies in El Encino mine in southwestern Mexico.

Projects in the volcanic terranes in the Trans-Mexican volcanic arc included investigations on potential geothermal sites. Some of the early studies included geophysical surveys in Los Azufres and Los Humeros calderas. In Los Humeros caldera paleomagnetic and aeromagnetic studies were included as part of a larger program to evaluate the geothermal potential of the site. The aeromagnetic survey documented a large dipolar magnetic anomaly over the central sector of the caldera, and small amplitude anomalies over the post-caldera volcanic cones (Flores-Luna et al., 1978). The paleomagnetic studies included magnetostratigraphy of the volcanic units, magnetic fabrics on the lava flows and siliceous domes and rock magnetic analyses.

10. Further Developments

In the following decades, the scope and number of studies in the laboratory has increased with new applications in geological and geophysical problems. Studies on stratigraphy and tectonics continued to develop, documenting occurrence of tectonic rotations and higher resolution paleoreconstructions. A group of projects that expanded was related to investigations on the Neoproterozoic glaciations (Urrutia-Fucugauchi and Tarling, 1983) and to mass extinctions and evolutionary turnovers (Urrutia-Fucugauchi, 1980e). The glaciations at the end of the Proterozoic were intense and might have affected high and low latitudes, and apparently exerted a major evolutionary force. After the glaciations, the fossil record documents presence of multi-cellular organisms in the Ediacaran period. The paleomagnetic studies provided evidence for low latitude likely global glaciated conditions and information on paleoclimatic and paleoenvironmental reconstructions (e.g., Urrutia-Fucugauchi and Tarling, 1983; Embleton and Williams, 1986). Paleomagnetic studies on



Figure 10. Examples of archaeometry studies (gravity, magnetic and seismic refraction surveys) in the Tenochtitlan archaeological remains in Downtown Mexico City.

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Precambrian tectonics and paleoreconstructions permitted to document the apparent polar wander curves for the major landmasses and their relationships with tectonics and climate (e.g., Embleton and Williams, 1986; Ballard et al., 1989; Indrum and Giggins, 1988). Studies on life evolution in the Phanerozoic focused on the mass extinction periods, and correlation and interrelationships among continental drift, continents/ oceans reconstructions, sea level changes, volcanism, and ocean-atmosphere interactions. Interest later concentrated on the mass extinction at the end of the Cretaceous and the events marking the Cretaceous/ Tertiary (K/T) boundary. The studies evolved to projects related to the impact theory and the Chicxulub crater (e.g., Urrutia Fucugauchi et al., 2011) and their implications for the evolution of planetary surfaces in the solar system (Urrutia-Fucugauchi & Perez Cruz, 2009). The studies on the K/T boundary and the Chicxulub impact are multi- and inter-disciplinary, involving a wide range of research fields. Paleomagnetic studies have played a major role, from the early magnetic polarity stratigraphic investigations on the Cretaceous and Tertiary carbonate sequences in Umbria, Italy that lead to documenting the geochemical markers of the impact, to the studies on the impact-generated lithologies in the Chicxulub crater and the K/T boundary sections worldwide.

Projects on applied geophysics on mineral exploration also expanded, with magnetic surveys over mining zones as well as potential prospects. Archaeomagnetic and archaeometry studies were carried out in several archaeological sites, including archaeological sites in central and western Mexico, the Yucatan peninsula and northern Mexico. One of the highlights include the ground magnetic surveys on Olmec sites that resulted in finding one of the colossal heads in the San Lorenzo Tenochtitlan site. Combined projects include the study of La Campana site that documented development of urban centers in western Mexico, far from the large urban and ceremonial centers in Mesoamerica. Studies in La Campana documented in particular the use of water supply and control systems. New projects included paleoclimatic and paleoenvironmental studies on Quaternary sedimentary sequences, which combined paleosecular variation and rock magnetic analyses. The paleoclimatic and paleoenvironmental studies have recently expanded to investigations on marine sediments, permitting development of new research areas, which are strongly multi-disciplinary (Perez Cruz, 2006; Perez Cruz & Urrutia-Fucugauchi, 2010).

The instrumental facilities and methods for paleomagnetic and rock magnetic research evolved rapidly in the 1970's and 1980's, particularly with the introduction of desk computers and new electronics (Collinson, 1983). The analytical facilities of the El Pozo laboratory in the following decades have expanded to include new instruments, in particular higher sensitivity magnetometers, magnetic anisotropy kappa bridges, ovens for paleointensity determination, and alternating field demagnetizers. Instruments for rock magnetic analyses include pulse magnetizers for isothermal remanent magnetization (IRM) acquisition and back-field demagnetization, Bartington instrument for determining susceptibility versus temperature curves, and the MicroMag system for magnetic hysteresis. The number of paleomagnetic laboratories and groups in paleomagnetism, rock magnetism and geomagnetism has continued to increase in Mexico and in Iberoamerica. As the field has evolved, the range of topics and themes being investigated has also expanded considerably. The creation of the LatinMag Association is a reflection of the expanding field, research activities and maturity in the region.

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