Sedimentology and stratigraphy of the Upper Cretaceous-Paleocene El Molino Formation, Eastern Cordillera and Altiplano, Central Andes, Bolivia: implications for the tectonic development of the Central Andes

Richard John Fink
Louisiana State University and Agricultural and Mechanical College

Follow this and additional works at: https://digitalcommons.lsu.edu/gradschool_theses
Part of the Earth Sciences Commons

Recommended Citation

This Thesis is brought to you for free and open access by the Graduate School at LSU Digital Commons. It has been accepted for inclusion in LSU Master's Theses by an authorized graduate school editor of LSU Digital Commons. For more information, please contact gradetd@lsu.edu.
SEDIMENTOLOGY AND STRATIGRAPHY OF THE UPPER CRETACEOUS-
PALEOCENE EL MOLINO FORMATION, EASTERN CORDILLERA AND
ALTIPLANO, CENTRAL ANDES, BOLIVIA: IMPLICATIONS FOR THE
TECTONIC DEVELOPMENT OF THE CENTRAL ANDES

A Thesis
Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College

in partial fulfillment of the
requirements for the degree of
Master of Science

in

The Department of Geology and Geophysics

by
Richard John Fink
B.S., Montana State University, 1999
August 2002
ACKNOWLEDGEMENTS

I would like to thank Drs. Bouma, Ellwood and Byerly for allowing me to present and defend my M.S. thesis in the absence of my original advisor. Drs. Brian Horton (University of California, Los Angeles) and William Devlin (ExxonMobil Exploration) were instrumental in my development as a scientist and critical thinker. I would like to thank Brian Hampton for providing valuable advice and commentary at all stages of this project. Brian Lareau supplied additional remarks during the project development and analysis phases of this thesis. I am immensely thankful to Dr. Sohrab Tawackoli of the Servicio de Geologia y Minas de Bolivia (La Paz) for logistical support and advice in support of fieldwork. Pedro Chuvata was extremely helpful as a driver, liason and field assistant. James Graber also provided valuable assistance with fieldwork. Conoco Inc. provided petrographic laboratory support.

This research was supported by National Science Foundation funds awarded to Dr. Brian Horton. Additional funding was provided by the Geological Society of America, American Association of Petroleum Geologists and Sigma Xi national grants-in-aid programs. Lastly, I would like to thank my parents, Henry J. Fink Jr. and Ilse R. Fink, and Bruce Miller for moral support and encouragement.
# TABLE OF CONTENTS

ACKNOWLEDGEMENTS ................................................................................................................................. ii

LIST OF TABLES ....................................................................................................................................................... v

LIST OF FIGURES ...................................................................................................................................................... vi

ABSTRACT .................................................................................................................................................................. viii

1. INTRODUCTION .................................................................................................................................................. 1
   1.1 Tectonic Overview ........................................................................................................................................ 2
   1.2 Upper Triassic(?)-Paleogene Stratigraphic Overview ................................................................................. 5
      1.2.1 Lower Succession Strata .................................................................................................................... 5
      1.2.2 Middle Succession Strata .................................................................................................................. 5
      1.2.3 Upper Succession Strata .................................................................................................................. 10

2. CRITERIA FOR DISTINGUISHING TECTONIC SETTING ................................................................................. 13
   2.1 Rift Basin Systems ........................................................................................................................................ 13
      2.1.1 Rift Basin Evolution ......................................................................................................................... 13
      2.1.2 Syn-Rift Recognition Criteria ......................................................................................................... 16
      2.1.3 Post-Rift Basin Recognition Criteria ............................................................................................. 19
   2.2 Retroarc Foreland Basin Systems ................................................................................................................ 19
      2.2.1 Foreland Basin System Evolution .................................................................................................... 19
      2.2.2 Foreland Basin Recognition Criteria ............................................................................................... 22

3. EL MOLINO FORMATION .................................................................................................................................... 26
   3.1 General Description ....................................................................................................................................... 26
      3.1.1 Regional Correlations ........................................................................................................................ 29
      3.1.2 Age Control ......................................................................................................................................... 30
      3.1.3 Depositional Environment—Previous Work ..................................................................................... 30
   3.2 Depositional Environment—This Work ......................................................................................................... 32
      3.2.1 FA1 Open Water Facies .................................................................................................................... 32
      3.2.2 FA2: Nearshore Facies ...................................................................................................................... 41
      3.2.3 FA3 Beach, Bar and Shoal Facies ..................................................................................................... 49
      3.2.4 FA4: Floodplain Facies ..................................................................................................................... 55
      3.2.5 FA5: Fluvial Facies ............................................................................................................................ 62
   3.3 Discussion ..................................................................................................................................................... 68

4. PALEOCURRENT DIRECTIONS AND PROVENANCE ......................................................................................... 72
   4.1 Methods and Background Data .................................................................................................................. 72
   4.2 Description .................................................................................................................................................. 76
   4.3 Interpretation ............................................................................................................................................... 81
   4.4 Discussion ............................................................................................................................................... 82

5. CONCLUSIONS .................................................................................................................................................... 85
LIST OF TABLES

2-1 Recognition criteria for syn-rift, post-rift and foreland basin settings .................. 14
3-1 Table showing lithofacies codes used in subsequent stratigraphic columns ........ 36
4-1 Table showing point count parameters.................................................................. 74
4-2 Table showing raw thin section point count data.................................................. 75
4-3 Table showing raw clast count data....................................................................... 77
### LIST OF FIGURES

1-1 Digital elevation and schematic maps showing the field area .................................. 3
1-2 Cross-sectional diagram of the Central Andes .......................................................... 4
1-3 Chronostratigraphic column showing Cretaceous Bolivia strata ......................... 6
1-4 Photo of La Puerta Formation ................................................................................. 7
1-5 Photo showing eolian cross-bedding within the La Puerta Formation .................... 8
1-6 Photo showing igneous intrusion within the La Puerta Formation ....................... 9
1-7 Photo of middle succession strata at the Miraflores Syncline ............................... 11
1-8 Photo of the Chaunaca and El Molino Formations ................................................. 12
2-1 Illustration showing the evolution of active and passive rifts ............................... 15
2-2 Illustration showing the key components of a foreland basin system ................... 21
3-1 Photo showing silicified gastropods used for stratigraphic correlations .............. 27
3-2 Close-up photograph of silicified gastropods ....................................................... 28
3-3 Base map showing the location of stratigraphic sections .................................... 33
3-4 Graphic representation of FA1 .............................................................................. 34
3-5 Legend for stratigraphic columns ......................................................................... 35
3-6 Regional distribution of FA1 .................................................................................. 38
3-7 Graphic representation of FA2 .............................................................................. 42
3-8 Photo showing mud cracks in massive limestone beds ......................................... 43
3-9 Photo showing a theropod trackway in FA2 strata ................................................. 44
3-10 Photo showing mammilated stromatolites in FA2 strata ..................................... 45
3-11 Regional distribution of FA2 ................................................................................ 46
3-12 Graphic representation of FA3 strata .................................................................... 50
3-13  Photo of horizontally-laminated and low angle trough cross beds in FA3 .......... 51
3-14  Photo of fossiliferous packstone in FA3 ......................................................... 52
3-15  Regional distribution of FA3 ................................................................. 54
3-16  Graphic representation of FA4 ................................................................. 56
3-17  Photo of FA4 paleosol ............................................................................. 58
3-18  Photo of amalgamated carbonate nodules ................................................. 59
3-19  Regional distribution of FA4 ................................................................. 60
3-20  Graphic representation of FA5 ................................................................. 63
3-21  Photo of FA5 lenticular sandstone bed ....................................................... 64
3-22  Photo of horizontally-laminated sandstone ............................................... 65
3-23  Regional distribution of FA5 ................................................................. 67
4-1   Map showing paleocurrent data and clast count summaries ......................... 78
4-2   Ternary diagrams showing sandstone composition ..................................... 79
5-1   Summary diagram showing facies and distributions .................................... 86
ABSTRACT

The Upper Cretaceous-Paleocene El Molino Formation of the Bolivian Central Andes consists of mixed siliciclastic and carbonate strata alternately interpreted as syn-rift, post-rift thermal sag and foreland basin deposits. These deposits can be divided into two lithostratigraphic sequences. The first sequence consists of a carbonate, carbonate sand and mudrock lower member, a middle member consisting entirely of mudrock and an upper member containing carbonates and mudrocks. The second lithostratigraphic sequence contains a lower member composed of carbonate sands, carbonates and mudrocks, and an upper member consisting of a coarsening upwards sequence of sandstones and mudrocks.

Within these lithostratigraphic sequences, five facies associations can be identified: 1) an open water facies; 2) a nearshore facies; 3) a beach, bar and shoal facies; 4) a floodplain facies; and 5) a fluvial facies. A regional study of El Molino Formation stratigraphic stacking patterns and facies association geographic distributions suggests that deposition occurred within a dominantly lacustrine basin. For most of El Molino Formation deposition, the lacustrine system remained hydrologically-closed and perennial, although evidence indicates that depositional systems experienced periodic ephemeral lacustrine conditions as well as hydrologically open lacustrine and/or shallow marine depositional environments. While lacustrine systems exist in syn-rift, post-rift thermal sag and foreland basin systems, sedimentological and stratigraphic data, in addition to an absence of key indicators of tectonic activity (e.g. faulting, growth strata) limit the El Molino Formation tectonic setting to post-rift thermal sag and/or foreland basin back-bulge settings. Paleocurrent and provenance data further support the
interpretation for post-rift thermal sag and/or back-bulge basin deposition, indicating flow of continental block provenance sediment into a central depositional basin while clast count data show a simple unroofing sequence indicative of the tectonic quiescence associated with post-rift thermal sag and foreland basin back-bulge tectonic settings.
1. INTRODUCTION

Sedimentary basins form in response to subsidence of the earth’s crust (Allen and Allen 1990). Different subsidence mechanisms vary with different tectonic settings, producing different characteristic basin geometries. For example, normal fault-controlled subsidence characteristic of rift settings produces relatively narrow, elongate, simple fault-bound basins normal to the axis of maximum extension. Alternately, flexural subsidence in compressional fold-thrust belt systems creates broad foreland basin systems that thin away from the fold-thrust belt load.

Sedimentary basin geometry is a prominent factor governing distribution of sedimentary facies, basin fill provenance, and paleoflow within the basin (Eisbacher et al. 1974; Cant and Stockmal 1989; Flemings and Jordan 1989; Owen and Crossley 1989; Jordan and Flemings 1991; Large and Ingersoll 1997). When preserved, these basin fill characteristics act as a proxy record of basin evolution, allowing the reconstruction of past tectonic events (DeCelles 1986; Crossley et al. 1992; Horton and DeCelles 2001).

The tectonic events governing deposition of the Upper Cretaceous-Paleocene El Molino Formation of the Central Andes (Bolivia) have been attributed to syn-rift (Viramonte et al. 1999), post-rift (Welsink et al. 1995; Mertmann and Fiedler 1997), and foreland basin settings (Sempere 1994, 1995; Sempere et al. 1997). This study tests these three competing hypotheses by reconstructing the El Molino Formation depositional system, basin geometry, and tectonic evolution from 16 regionally-distributed measured stratigraphic sections totaling 4440 m, 19 paleocurrent measurement stations (n = 185), 10 conglomerate clast counts (n = 1107) and 23 sandstone thin-sections.
1.1 Tectonic Overview

The modern Central Andes (Figs. 1-1, 1-2) consists of five distinct physiographic provinces: 1) the Western Cordillera, an active magmatic arc; 2) the Altiplano Plateau, a crustal-scale piggyback basin; 3) the Eastern Cordillera, the deformed thrust belt core; 4) the Subandean zone, the active fold-thrust belt; and 5) the Chaco and Beni Plains and Pantanal Wetlands, the modern, undeformed foreland basin (Jordan et al. 1983; Isaacks 1988; Horton and DeCelles 1997; McQuarrie and DeCelles 2001).

The evolution of these physiographic provinces began with the onset of subduction-related east-stepping magmatic arc development during late Paleozoic-Early Mesozoic time (Forsythe 1982; Herve et al. 1987; Ramos 1988; Coney and Evenchick 1994; Viramonte et al. 1999). During the late Permian-Triassic periods, extensional rift basins developed in western Chile and central Peru, continuing into Cretaceous time with new rift basins forming in northern Argentina and Bolivia (Gallinski and Viramonte 1988; Comignuez and Ramos 1995; Sempere 1995; Welsink et al. 1995; Sempere et al. 2002). Paleozoic basement rocks and Mesozoic pre-rift, syn-rift and, post-rift strata were subsequently uplifted during the late Cretaceous-Paleocene formation of an eastward-migrating retroarc foreland basin system (Sempere 1994, 1995; Horton and DeCelles 1997; Sempere et al. 1997; Horton et al. 2001). During late Eocene to early Miocene time, west vergent backthrusting at the western edge of the Eastern Cordillera created a crustal-scale piggyback basin between the backthrust belt and the Western Cordilleran volcanic arc (McQuarrie and DeCelles 2001). Meanwhile, the east vergent foreland basin system migrated to its current position in the Subandean Zone, Chaco and Beni Plains and Pantanal Wetlands.
Figure 1-1. Digital elevation and schematic map showing study area (boxed area) and the physiographic provinces of the Bolivian Central Andes. Cool colors (blue and purple) represent low elevation topography while hot colors (yellow and red) represent high elevation. The flat green topography adjacent to the South American orocline represents the ~3.8 km-high Altiplano Plateau (DEM image produced by Cornell Andes Project). Graphic map modified from Hampton (2002).
Figure 1-2. Cross-sectional diagram showing the relative elevation of Central Andean physiographic provinces (names on top) and the general tectonic scenario (Modified from Hampton 2002).
1.2 Upper Triassic(?)-Paleogene Stratigraphic Overview

Upper Triassic(?)-Paleogene basin deposits of the Puca Group in the Eastern Cordillera and Altiplano (Fig. 1-3) include: 1) a lower succession dominated by regionally extensive, Upper Triassic(?) to Lower Cretaceous sandstone; 2) a middle mudrock, carbonate, and evaporite succession deposited in restricted, localized basins; and 3) a regionally extensive upper succession consisting of carbonate rocks, mudrock and sandstone.

1.2.1 Lower Succession Strata

Lower succession rocks consist of the poorly dated Triassic-Lower Cretaceous La Puerta Formation and equivalent units (Kosmina, Macha, Ravelo and Sucre Formations) are present throughout the study area (Viramonte et al. 1999). These rocks unconformably overlie Paleozoic basement rocks, consisting of up to 1350 m of sandstone with rare >200 m thick basal conglomerate rocks. Basal conglomerate rocks include basalt and Paleozoic basement rock clasts while sandstone beds exhibit ubiquitous trough cross-stratification interpreted as braided fluvial deposits and ~10 m thick cross-beds suggesting an eolian environment (Figs. 1-4, 1-5) (Cherroni 1977; Sempere, 1994; Mertmann and Fiedler, 1997). Basalt flows (Fig. 1-6), and rare volcanic dikes interbed with and crosscut lower succession rocks. In addition, Sempere (1994) reports normal faulting of lower succession rocks north at Otavi.

1.2.2 Middle Succession Strata

Strata of the middle succession unconformably overlie lower succession rocks and include the Lower to Upper Cretaceous Condo, Tarapaya, Miraflores, Aroifilla, Torotoro
Figure 1-3a. Chronostratigraphic column relating Cretaceous stratigraphy to age data and episodes of volcanism and faulting. Grey shaded area highlights the El Molino Formation. Note that the formations listed consist of the prevalent formations in the area of interest and does not contain the formation names of all stratigraphic equivalents in the Bolivian Central Andes. Figure 1-3b, Magnetostratigraphic column comparing magnetostratigraphic chron with relative stratigraphic level within the El Molino Formation. Note that the magnetostratigraphic column is hinged on two Ar-Ar dates of 71.6 and 72.6 Ma below the 25m level of the El Molino Formation, and lacks correlative age control above these two isotopic dates. Paleomagnetic, isotopic and palynological age data compiled from Viramonte et al. (1999) and Sempere et al. (1997). Fossil information derived from Gayet et al. (1991, 1993, 2001) and Marshall et al. (1997). Fault data taken from Sempere (1994). Figure 1-3b is modified from Sempere et al. (1997).
Figure 1-4. Outcrop exposure of lower succession La Puerta Formation at the Mira-flores Syncline northwest of Potosi. Note that the obvious cliff-former in the foreground, as well as the less exposed sandstone strata forming the ridgeline, both represent La Puerta Formation strata.
Figure 1-5. Eolian cross-bedding in La Puerta Formation sandstones at the town of Betanzos located approximately 35 km west of Potosí. Scale person is approximately 1.8 m tall.
Figure 1-6. Igneous intrusion within the La Puerta Formation at Incapampa.
and Chaunaca Formations with a total thickness >1800 m in some locations (Figs. 1-7, 1-8) (Sempere 1995; Viramonte et al. 1999). These rocks can be divided into four lithofacies groups: 1) brown mudrock (Tarapaya Formation) with a rare basal conglomerate (Condo Formation) interpreted as alluvial to lacustrine deposits (Sempere 1994); 2) carbonate beds with minor mudrock interbeds (Miraflores Formation) representing a rapid shallow marine transgression (Sempere 1994); 3) red to green mudrock intercalated with minor evaporite beds, sandstone, carbonate rocks, conglomerate, volcanic flows and tuff beds (Aroifilla and Chaunaca Formations) interpreted as distal alluvial to playa lake deposits (Mertmann and Fiedler 1997; Sempere et al. 1997); and 4) red sandstone with volcanic flows (e.g., Maragua) and conglomerates containing basalt clasts (Torotoro Formation) representing alluvial plain deposition (Marshall et al. 1997; Sempere et al. 1997).

1.2.3 Upper Succession Strata

Upper succession rocks conformably overlie middle succession rocks or unconformably onlap lower succession or Paleozoic basement rocks (Fig. 1-8). This stratigraphic interval reaches thickness >1000 m and includes the Upper Cretaceous-Paleocene El Molino, Santa Lucia and Impora Formations (Sempere et al. 1997). Upper succession rocks consist of mudrock, carbonate, sandstone, evaporite, and tuff beds, and have been interpreted as lacustrine, shallow marine, fluvial and alluvial deposits (Sempere et al. 1997; Gayet et al. 2001).
Figure 1-7. Photograph of middle succession rocks including reddish-brown Tarapaya Formation mudrock and whitish-yellow Miraflores Formation limestone at the Miraflores syncline northwest of Potosi. The lower succession La Puerta Formation forms the upper ridgeline and part of the dip-slope.
Figure 1-8. Foreground rocks represent the basal "green" layer of the middle succession Chaunaca Formation. Reddish-violent background rocks belong to the Chaunaca Formation while resistant yellow-beige rocks form the base of the upper succession El Molino Formation. Scale person is ~1.8m.
2. CRITERIA FOR DISTINGUISHING TECTONIC SETTING

Distinguishing tectonic environments from the rock record can be difficult. The contrasting tectonic interpretations for El Molino Formation deposition underscore this statement. In order to discern between tectonic settings for the El Molino Formation, an understanding of tectonic basin evolution and associated recognition criteria is required. The following describes the tectonic evolution and recognition criteria (Table 2-1) for syn-rift, post-rift and retroarc foreland basin deposits.

2.1 Rift Basin Systems

2.1.1 Rift Basin Evolution

Continental rifts represent the crustal manifestation of lithospheric extension. Lithospheric extension results from active or passive driving forces within the asthenosphere (McKenzie 1978; Sengor and Burke 1978; Ruppel 1995). Active rifting (Fig. 2-1) occurs in response to the “active” impingement of asthenospheric material upon the base of the lithosphere (Sengor and Burke 1978; Ruppel 1995). Buoyant magmatic plumes rise through denser asthenospheric material, exerting a normal force upon the base of the lithosphere (Fig. 2-1a) (Ruppel 1995). The lithosphere responds to this normal force by upwarping and thinning, forming a characteristic crustal dome (Fig. 2-1b) (Neugebauer 1978; Sengor and Burke 1978; Ruppel 1995). As the magmatic plume continues to impinge upon the lithosphere, large volumes of melt are produced and subsequently extruded (Fig. 2-1b) (Ruppel 1995). Crustal extension follows magmatism, forming rapidly subsiding normal fault bound syn-rift basins (Fig. 2-1c) (Ruppel 1995; Crossley and Cripps 1999). Examples of active rifts include the West Antarctic, East African, Ethiopian and Rio
Table 2-1. Table showing recognition criteria for discriminating between syn-rift, post-rift thermal sag and foreland basin systems.

<table>
<thead>
<tr>
<th></th>
<th>Syn-Rift Basin</th>
<th>Post-Rift Thermal Sag Basin</th>
<th>Foreland Basin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural Style</td>
<td>Normal faulting common within half- and full-graben basins.</td>
<td>Devoid of structures.</td>
<td>Thrust faulting common in wedge-top depozone. Localized normal faulting reported for forebulge depozones.</td>
</tr>
<tr>
<td>Volcanism</td>
<td>Tholeiitic and alkaline volcanism.</td>
<td>Possible volcanism but not characteristic of environment.</td>
<td>Possible volcanism but not characteristic of environment.</td>
</tr>
</tbody>
</table>
| Basin Geometry           | Basins typically consist of a series of narrow (20-50 km), long (50-100 km) basins connected by transform zones. Segments reach depths of 6-10 km. | Basins show lens-like geometry in cross-section normal to and centered over syn-rift depositional centers. | Foredeep depozones tend to form deep, elongate basins. Forebulge depozones form topographic highs. Back-bulge basins are commonly broad and shallow.
| Subsidence Curve         | Rapid subsidence.                                                             | Subsidence curve shows inverse logarithmic geometry.                           | Subsidence curve appears approximately sigmoidal in geometry.                   |
| Provenance               | Continental block provenance characterized by high quartz content.            | Continental block provenance characterized by high quartz content.              | Recycled orogen provenance characterized by quartz and plagioclase feldspar content. |
Figure 2-1. Figure showing the differences between active and passive rifting processes. Active rifting processes begin with a phase of mantle impingement on the base of the crust, magmatism, uplift and subsequent fault-related extension (steps a through c). Passive rifting processes start with the lithospheric extension, then fault-related extension followed by mantle upwelling and associated uplift and magmatism (steps d through f). Figure is modified from Ruppel (1995).
Grande rifts (Sengor and Burke 1978; Fairhead 1986; Reading 1986; Leeder 1995; Ruppel 1995).

Passive rifting (Fig. 2-1) initiates in response to shear stress caused by plate boundary interactions or sublithospheric convective drag (Ruppel 1995). Crustal normal faulting follows lithospheric extension, generally forming along preexisting zones of weakness (Fig. 2-1d). As the lithosphere thins in response to extension, asthenospheric material upwells beneath the thinned lithosphere (Fig. 2-1e). Magmatism commonly follows asthenospheric upwelling, underplating the crust or emplacing magma at or near the surface (Fig. 2-1f). Lastly, late-stage epeirogenic doming may occur (e.g., Oslo Rift) although doming is not a defining characteristic of passive rifting (McKenzie 1978; Rohrman et al. 1994; Ruppel 1995). The Baikal Rift, Oslo Rift, West and Central African Rift System, Gediz Graben, Basin and Range Provinces, and Rhine Graben are all examples of passive rifting (McKenzie 1978; Sengor and Burke 1978; Reading 1986; Rohrman et al. 1994).

Post-rift basins result from the thermal relaxation of the lithosphere after syn-rift thinning and heating. During syn-rift crustal thinning, lithospheric temperatures are elevated, causing lithospheric expansion. Once the syn-rift heat source abates, the lithosphere cools and contracts, creating broad, post-rift basins centered over the syn-rift grabens (Sclater and Christie 1980).

2.1.2 Syn-Rift Recognition Criteria

Several recognition criteria allow for the identification of syn-rift tectonic settings: 1) a pre- or post-rift unconformity; 2) tholeiitic to alkaline volcanism; and 3) normal faulting. The pre-rift unconformity forms during the initial doming phase of
active rift systems while rare post-rift unconformities occur during late stage passive rifting. Although tholeiitic to alkaline volcanism commonly occurs in many rift sequences, volcanism alone is not a reliable indicator of rift development (Sengor and Burke 1978; Reading 1986; Friedmann and Burbank 1995; Crossley and Cripps 1999). Many rift systems lack significant volcanic rocks, and where present, volcanism is concentrated along the rift axis (Crossley and Cripps 1999; Le Turdu et al. 1999).

Normal faulting occurs within both active and passive rift systems, however fault timing varies between systems. Active rift systems form normal faults towards the end of the rift cycle, subsequent to the onset of crustal doming and magmatism. Normal faulting in passive systems represents an early stage of rift development, preceding magmatism and possible epeirogenic uplift. In either case, normal faults constitute a primary characteristic of rift basins, defining basin geometry, acting as the major subsidence mechanism and exerting considerable control over the location of sedimentary facies (Gupta et al. 1998).

Intracontinental rift basins typically consist of a series of long (50-100 km), narrow (20-50 km) fault-bound asymmetric half-graben segments linked by strike-slip fault zones (Reading 1986; McHargue et al. 1992; Friedmann and Burbank 1995). Half-graben rift basin extension usually persists for >10 Ma (30-40Ma), potentially evolving into full horst-graben systems (Wilson 1989; Friedmann and Burbank 1995; Scholz et al. 1998; Le Turdu et al. 1999). However, total rift basin extension rarely exceeds 20% or a stretching factor (β-factor) of 1.2. Subsequent basin subsidence initiates with a very brief, early stage of slow subsidence followed by a lengthier phase of rapid, fault-induced
subsidence generating basins with up to 6-10 km of accommodation space (Friedmann and Burbank 1995; Gupta et al. 1998).

Sediment accumulation within subsiding syn-rift basins varies with distance from the basin-bounding normal fault. The hanging wall immediately adjacent to the footwall marks the axis of maximum syn-rift subsidence (Cohen 1990). Due to rapid subsidence, this zone consists of short, steep, footwall-derived drainage systems, commonly producing thick, small area, rarely coalescing fan delta and alluvial fan deposits (Ingersoll 1988; Cohen 1990; Mack and Seager 1990). Footwall-derived fan deltas and alluvial fan deposits commonly contain poorly sorted, monomictic pre-rift sediment (Cohen 1990; Crossley and Cripps 1999). In deepwater systems, footwall-derived, dominantly coarse-grained turbidity flows are also common (Cohen 1990; Lambiase 1990; Scholz 1990; Leeder 1995).

Footwall-derived fan deltas, turbidity flows and alluvial fans interfinger with hanging wall-derived fine-grained deepwater, playa lake or fluvial deposits (Owen and Crossley 1989; Mack and Seagar 1990; Johnson and Ng’ang’a 1990; Friedmann and Burbank 1995). Hanging wall-derived deposits vary considerably, including lacustrine and marine siliciclastic and carbonate sediments in addition to fluvio-deltaic, fluvial and alluvial fan deposits (Ingersoll 1988; Cohen 1990; Friedmann and Burbank 1995). Hanging wall alluvial fans tend to be broader in dimension and finer-grained than footwall-derived alluvial fan strata, receiving sediment from large, low relief drainage systems (Ingersoll 1988; Cohen 1990; Mack and Seagar 1990). Because of low hanging wall relief, changes in climate or subsidence rates trigger rapid changes in basin facies distribution (Cohen 1990).
2.1.3 Post-Rift Basin Recognition Criteria

Post-rift basins consist of broad, relatively shallow saucer-shaped basins centered over syn-rift deposits (Sclater and Christie 1980; McHargue et al. 1992; Henry et al. 1996; van Wees et al. 1996). For example, North Sea post-rift basins contain 1100-1400 m of strata at basin center, thinning to 600-700 m towards the flanks and cover an area 200-300 km wide by 600 km long (Sclater and Christie 1980). Normal faults associated with syn-rift tectonism are absent (Sclater and Christie 1980; Henry et al. 1996). Post-rift basin strata include shallow marine, lacustrine or fluvial facies deposits (Sclater and Christie 1980; McHargue et al. 1992; Crossley and Cripps 1999). Other examples of post-rift basins include the West African Kwanza, and East Brasil Rift basins (Sclater and Christie 1980; Henry et al. 1996).

2.2 Retroarc Foreland Basin Systems

2.2.1 Foreland Basin System Evolution

Retroarc foreland basin systems represent regions of potential sediment accommodation that develop on continental crust between subduction-related compressional fold-thrust belts and cratons (Dickinson 1974; Beaumont 1981; Jordan 1981; DeCelles and Giles 1996). Sediment accommodation space in retroarc foreland basin systems results from flexure of the continental lithosphere by orogenic and sediment loading (Jordan 1981; Beaumont 1981) in addition to dynamic subsidence (Mitrovica et al. 1989; Gurnis 1992). Orogenic and sediment loading generates a flexural wave normal to the fold-thrust front, generally migrating cratonward with the advance of the orogenic belt over 10’s of millions of years (Flemings and Jordan 1990; DeCelles and Currie 1996). In addition to wave effects resulting from orogenic and sediment loading,
the rate of fold-thrust belt advancement also effects foreland basin wavelength (Flemings and Jordan 1989). Rapid thrusting produces short wavelength, high amplitude foreland basins while slow thrust rates generate long wavelength, low amplitude foreland basins (Flemings and Jordan 1989).

The basin geometry produced by the flexural wave can be divided into wedge-top, foredeep, forebulge and back-bulge depozones (Fig. 2-2)(DeCelles and Giles 1996). The wedge-top depozone consists of depositional basins within the orogenic belt and extends cratonward to the forward-most extent of frontal thrust deformation (DeCelles and Giles 1996). Foredeep deposits accumulate within the high amplitude, flexurally down-warped basin adjacent between the orogenic load and the positive amplitude forebulge (DeCelles and Giles 1996). The positive amplitude forebulge is a theoretical model-driven construct. Load-driven flexural models using an elastic lithosphere indicate the existence of a forebulge at a distance of $\pi \alpha$ (for an infinite plate) or $3\pi \alpha/4$ (for a broken plate) normal to the axis of loading, where $\alpha$ is defined as the flexural parameter that describes the relationship between flexural rigidity and the density contrast between mantle and basin fill (DeCelles and Giles 1996). Evidence for forebulge existence consists of Bouguer gravity highs, stratigraphic onlap patterns and normal faulting present at or about the predicted axis of the forebulge (Coudert et al. 1995; Horton and DeCelles 1997; Currie 1998; Hudson 2000). The forebulge depozone consists of strata deposited upon or immediately adjacent to this theoretical positive relief feature (DeCelles and Giles 1996).

Cratonward of the forebulge depozone lies the broad wavelength, shallow, negative amplitude back-bulge depozone (DeCelles and Giles 1996). While foredeep
Figure 2-2. Illustration showing the key components and theoretical depozones within a foreland basin system. Note the overall wedge-shaped basin fill geometry (dotted area). Modified from DeCelles and Giles (1996).
Depozone accommodation space primarily results from orogenic and sediment loading of continental lithosphere, some deposits attributed to back-bulge deposition show (e.g., Morrison Formation in Utah) thicker accumulations of strata than predicted by load-driven flexural models (DeCelles and Currie 1996; DeCelles and Giles 1996; Currie 1998). Similarly, some foredeep depozones also exhibit unusual basin amplitudes unexplainable by simple flexure beneath observed topographic and basin fill loads (DeCelles and Giles 1996). These inconsistencies may represent the effects of dynamic subsidence resulting from viscous-coupling of continental lithosphere with mantle material entrained by a subducting oceanic slab (Mitrovica et al. 1989; Gurnis 1992; DeCelles and Currie 1996; DeCelles and Giles 1996). The effects of dynamic subsidence can generate kilometer-scale subsidence at wavelengths extending 1000 km or more from the trench (Mitrovica et al. 1989), potentially generating constructive or destructive interference between load-driven flexural waveforms and dynamic subsidence-related flexural waves (DeCelles and Giles 1996).

2.2.2 Foreland Basin Recognition Criteria

With the competing influences of load-driven and dynamic flexural subsidence, the presence of orogenic belt thrust and reverse faults and potential forebulge normal faulting, recognition of foreland basin systems from ancient stratigraphic deposits can be challenging. A first order glance shows that foreland basin strata form a doubly tapered wedge-shaped geometry in cross-section (Fig. 2-2) (DeCelles and Giles 1996). Foreland basin depozones migrate with the fold-thrust belt, successively replacing one another in an upwards-coarsening sequence that potentially records the passage of each stratigraphic
depocenter (DeCelles and Currie 1996; DeCelles and Giles 1996; Horton and DeCelles 1997).

Straddling the fold-thrust belt and extending cratonward to the frontal tip of thrust belt deformation, the wedge-top depozone is characterized by an abundance of fault- and fold-related growth structures and unconformities indicating deposition within the deformation front (DeCelles and Giles 1996; Horton and DeCelles 1997). Wedge-top sediments commonly contain coarse-grained, texturally and compositionally immature sediment derived directly from the thrust belt (DeCelles and Giles 1996). Subaerial wedge-top strata include coarse-grained alluvial and fluvial sediments while subaqueous strata consist of fine-grained shelf and lacustrine sediments and mass flow deposits (DeCelles and Giles 1996).

Cratonward of the wedge-top depozone, the foredeep depozone accumulates sediment shed from the thrust front and, more rarely, sediment eroded from the magmatic arc, forebulge and/or craton (Dickinson 1974; DeCelles and Giles 1996). Foredeep provenance typically depends upon the pre-orogenic history of strata involved in orogenic folding and thrusting (Dickinson 1974; Dickinson and Suczek 1979). Thickest stratal accumulations occur adjacent to the wedge-top depozone, commonly reaching 2-8 km in depth and tapering towards the forebulge 100-300 km away (Flemings and Jordan 1989; DeCelles and Giles 1996). Subaerial foredeep depocenters often contain fluvial megafans showing transverse paleoflow and axial fluvial systems fed by tributaries from the thrust front and craton (Cant and Stockmal 1989; Flemings and Jordan 1989; DeCelles and Giles 1996; Horton and DeCelles 1997). Deposition within subaqueous foredeep depozones consists of shallow water (< 200m) siliciclastic and carbonate shelf
deposits (DeCelles and Giles 1996; Gupta and Allen 2000). Where both subaqueous and
subaerial settings coexist, the transitional zone commonly contains large delta deposits
(DeCelles and Giles 1996).

At the cratonward edge of the foredeep, the forebulge depozone consists of a
positive amplitude feature 60-470 km wide and 10s to 100s of meters high that separates
the foredeep from the back-bulge depozone (DeCelles and Giles 1996). The topographic
expression of the forebulge may be suppressed by burial and flexural loading beneath
sediment shed from the thrust belt (Flemings and Jordan 1989). The forebulge depozone
typically represents a zone of limited or condensed deposition commonly accompanied
by paleosol development, or an area of non-deposition resulting in an unconformity
(Jacobi 1981; Cant and Stockmal 1989; Flemings and Jordan 1990; DeCelles and Giles
1996; Currie 1998). Stratal thinning, onlap and the presence of local normal-fault bound
depositional centers also characterize forebulge depozones (DeCelles and Giles 1996;
Hudson 2000). In subaqueous environments, carbonate ramps and reefs may form on the
forebulge (DeCelles and Giles 1996; Ver Straeten and Brett 2000).

Subaqueous carbonate ramps and reefs may also extend into the back-bulge
depocenter in addition to other shallow marine sediments (DeCelles and Currie 1996;
DeCelles and Giles 1996; Ver Straeten and Brett 2000). Subaerial back-bulge deposits
largely consist of fine-grained sediment transported from the fold-thrust belt but cratonic
and forebulge sources may be important sediment contributors as well (DeCelles and
within the continental block and recycled orogen provenance fields of Dickinson and
Suczek (1979) suggesting orogenic belt and cratonic sediment contributions. Although
fine-grained fold-thrust belt strata tend to dominate back-bulge deposition, coarse-grained deposits adjacent to the flank of the uplifted forebulge deposystem may also be present (DeCelles and Giles 1996; Currie 1998). Back-bulge deposits reach thickness greater than 250 meters, contradicting flexural model predictions (DeCelles and Currie 1996; Horton and DeCelles 1997; Currie 1998) although additional accommodation space may result from dynamic subsidence (Mitrovicia et al. 1989; Gurnis 1992). These deposits typically accumulate within elongate, closed basins (DeCelles and Giles 1996; Horton and DeCelles 1997).
3. EL MOLINO FORMATION

3.1 General Description

The upper succession El Molino Formation contains a complex association of Maastrichtian-Paleocene mudrocks, carbonate strata, sandstones and minor evaporite rocks. Basal El Molino Formation rocks are identified by the first calcareous sandstone or carbonate beds overlying the Chaunaca, Torotoro or La Puerta (and equivalent) Formations or older rocks (Lohmann and Branisa 1962; Fiedler and Mertmann 1997; Sempere et al. 1997). The lower contact between the El Molino and the Cretaceous Chaunaca/Torotoro Formations is conformable whereas unconformable (locally angular with <15°) contacts divide El Molino Formation strata from underlying La Puerta Formation and Paleozoic strata.

For the purpose of regional correlation of El Molino Formation strata, gastropod fossils proved extremely useful. The gastropods used for correlation are <5 cm long, <2 cm wide and have a spiral-shaped conical morphology (Figs. 3-1, 3-2). For a more detailed listing of El Molino Formation fossil content and related paleoenvironmental interpretations see Gayet et al. (1991, 1993, 2001) and Marshall et al. (1997).

At a scale of hundreds of meters, El Molino Formation rocks form two lithostratigraphic sequences. The first lithostratigraphic sequence (e.g., Torotoro, Ichilula sections, Appendix 1) consists of three lithostratigraphic members: 1) a lower member containing calcareous sandstone, carbonate and mudrock beds that forms the lower ~50% of a given stratigraphic section; 2) comprising ~35% of the stratigraphic section, the middle member is dominated by mudrock; and 3) an upper member consisting of
Figure 3-1. Photograph showing silicified gastropod fossils used for regional stratigraphic correlation within the El Molino Formation. Photograph taken at Incapampa locality.
Figure 3-2. Photograph showing a close-view of gastropod fossils used for regional stratigraphic correlation within the El Molino Formation. Photograph taken at Incapampa locality.
interbedded mudrock and carbonate strata that usually makes up the remaining ~15% of the section. This first lithostratigraphic sequence has been recognized and reported by previous workers and, with the exception of stratigraphic sections circa Lake Titicaca, commonly outcrops on the Altiplano and the western Eastern Cordillera (e.g., Marshall et al. 1997; Sempere et al. 1997). The second sequence (e.g., Jesus de Machaca, Incapampa sections, Appendix 1) contains a lower member characterized by calcareous sandstone, carbonate and mudrock beds (similar to the lower member of the first sequence) and transitions up section to an upper member consisting of sandstone and mudrock strata. The lower member typically comprises ~25% of the section. This second lithostratigraphic sequence occurs at sections near Lake Titicaca and in the eastern Eastern Cordillera.

Both sequences form transitional contacts with the overlying Santa Lucia Formation. This contact consists of a subtle color change from reddish-purple El Molino Formation mudrock to brick red Santa Lucia mudrock. Sempere et al. (1997) suggest that the transitional nature of the boundary results from changing climatic conditions.

3.1.1 Regional Correlations

The El Molino Formation has been correlated with the Bolivian Eslabon-Flora and Cajones Formations, Peruvian Vilquechico Formation, northwest Argentinian Yacoraite, Lecho, Tunal and Olmedo Formations, and the north Chilean Estratos de Quebrada Blanca de Poquis and Pajonales Formations (Cherroni 1977; Sempere et al. 1997). The presence of similar fossil faunas (e.g., the fish species Gasteroelupea branisae and Pucapristis branisi) support correlations between El Molino Formation

3.1.2 Age Control

The El Molino Formation represents the best-dated stratigraphic sequence in the entire Upper Triassic?-Paleocene Puca Group. Isotopic dates, magnetostratigraphy and fossil data (Fig. 1-3) place El Molino Formation deposition between Maastrichtian and Paleocene time. Two Altiplano tuffs from the basal 25m of the El Molino section yielded $^{40}\text{Ar}/^{39}\text{Ar}$ isotopic dates of $71.59 \pm 0.25$ Ma and $72.57 \pm 0.15$ Ma (Sempere et al. 1997). With these dates as a baseline, subsequent magnetostratigraphy places El Molino deposition between chron 32n and 26r (~73-60Ma) (Sempere et al. 1997). Fossil fauna collected south of Cochabamba further support these age data with 9 fossil taxa restricted exclusively to the Maastrichtian and 6 taxa limited to Maastrichtian-Paleocene time (Gayet et al. 2001).

3.1.3 Depositional Environment-Previous Work

The depositional setting of the El Molino Formation has been addressed in numerous studies (e.g., Gayet et al. 1993, 2001; Rouchy et al. 1993; Sempere 1994, 1995; Camoin et al. 1997; Sempere et al. 1997; Deconinck et al. 2000). These studies generated two competing hypotheses suggesting that El Molino Formation deposition occurred in either a non-marine lacustrine system with periodic outflow to marine waters (Rouchy et al. 1993; Camoin et al. 1997; Deconinck et al. 2000) or a lacustrine system that experienced periodic marine incursions (Gayet et al. 1993, 2001; Sempere 1994, 1995; Sempere et al. 1997).
The data used to support an exclusively non-marine hypothesis include: 1) \( \delta^{18}\)O (PDB) values of –14.2 to 2.8‰, and \( \delta^{13}\)C (PDB) values of –12.9 to 2.8‰ (Camoin et al. 1997); 2) \( \delta^{18}\)O and \( \delta^{13}\)C covariance (Camoin et al. 1997); and 3) dominance of terrestrial and freshwater fossil fauna (Rouchy et al. 1993; Camoin et al. 1997). While the preferred explanation for the stable isotope (\( \delta^{18}\)O and \( \delta^{13}\)C) data is that of non-marine deposition (Keith and Weber 1967; Platt 1989; Talbot 1990; Talbot and Kelts 1990), a marine depositional setting cannot be ruled out if based only on these data. Average \( \delta^{18}\)O values from Cretaceous (n=39) and Tertiary (n=63) marine limestones range from –4.49±1.85 to –2.99±2.37 while average \( \delta^{13}\)C values are from 0.25±3.44‰ to -1.51±2.77‰ (Keith and Weber 1967). El Molino Formation values for \( \delta^{18}\)O and \( \delta^{13}\)C are –14.2 to 2.8‰ and –12.9 to 2.8‰, respectively, thus failing to exclude a marine depositional setting.

Covariant \( \delta^{18}\)O and \( \delta^{13}\)C values are characteristic of hydrologically-closed lacustrine basin systems (Talbot 1990; Talbot and Kelts 1990). However, isotopic covariance has also been identified in restricted marine settings (Ingram et al. 1996). This result also demonstrates that \( \delta^{18}\)O and \( \delta^{13}\)C covariance fails to exclude marine deposition.

In support of a non-marine origin is the presence of non-marine fauna within El Molino Formation rocks, but this result still fails to exclude periodic marine conditions. Of the numerous faunal genera identified in the El Molino Formation, most are freshwater, brackish water or marine fauna capable of entering non-marine environments (Gayet et al. 1993, 2001; Rouchy et al. 1993; Camoin et al. 1997). However, at least one exclusively marine genus (Aulopiformes Enchodus) exists within El Molino Formation strata (Gayet et al. 2001). The presence of Aulopiformes Enchodus and the predominance of marine taxa within the El Molino Formation indicate episodic marine deposition.
(Gayet et al. 1993, 2001; Sempere et al. 1997). Although many of the marine taxa present could enter the El Molino Formation depositional system during periods of lacustrine outflow (Rouchy et al. 1993; Camoin et al. 1997), evidence supporting the existence of Aulopiformes Enchodus within non-marine waters would be required to fully debunk a marine-influenced depositional system hypothesis. Regardless of actual depositional conditions, the presence of marine fauna indicates that the El Molino Formation depositional system was at or near sea level.

The work cited above (Rouchy et al. 1993; Camoin et al. 1997; Sempere et al. 1997; Deconinck et al. 2000; Gayet et al. 2001) demonstrates the difficulties encountered when attempting to distinguish shallow marine from lacustrine deposits in the El Molino Formation. In order to simplify facies analysis for the El Molino Formation and to reflect the dominant lacustrine depositional signature (e.g., Rouchy et al. 1993; Camoin et al. 1997; Deconinck et al. 2000) lacustrine facies terminology has been adopted.

3.2 Depositional Environment - This Work

Observations from 16 regionally-distributed measured stratigraphic sections (Fig. 3-3) suggests that El Molino Formation strata consists of five facies associations (FA): 1) open water facies; 2) nearshore facies; 3) beach, bar and shoal facies; 4) floodplain facies; and 5) fluvial facies.

3.2.1 FA1 Open Water Facies

3.2.1.1 Description

Black, gray, brown and green 0.05-17m thick shale bedsets alternate with thickly laminated (3-10 mm thick) 0.02-0.14m thick yellow, gray and green carbonate mudstone bedsets (Figs. 3-4). Shale and carbonate mudstone beds have planar bounding surfaces
Figure 3-3. Map showing the location of measured stratigraphic sections, and major towns.
Figure 3-4. Graphic representation of FA1: Open water facies association. Lithologic legend and guide to lithology codes are shown in Figures 3-5 and Table 3-1.
Figure 3-5. Graphic legend showing lithologic symbols and conventions used in stratigraphic columns within this study. Note that sandstone and mudrock lithologies are further described by lithologic codes found in Table 3-1.
Table 3-1. Lithofacies codes used in stratigraphic columns throughout the text (Modified from Miall 1977). Note that lithofacies code Fr is used here to distinguish ripple cross-lamination in mudrocks rather than Miall's (1977) original usage to denote presence of root casts and mottling).

<table>
<thead>
<tr>
<th>Lithofacies Code</th>
<th>Lithofacies</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fsm</td>
<td>Massive mud- to very fine-grained material</td>
<td>Suspension fallout or weak traction transport of clay, mud, silt and very fine-grained material followed by subsequent destruction of primary sedimentary structures.</td>
</tr>
<tr>
<td>Fl</td>
<td>Horizontally laminated clay to very fine-grained material</td>
<td>Suspension fallout.</td>
</tr>
<tr>
<td>Fr</td>
<td>Ripple cross-stratified mudrock.</td>
<td>Migration of lower flow regime current ripples (unidirectional or bidirectional).</td>
</tr>
<tr>
<td>Fm</td>
<td>Massive mudrock with mud cracks</td>
<td>Suspension fallout or weak traction transport followed by dessication and shrinkage.</td>
</tr>
<tr>
<td>Sr</td>
<td>Ripple cross-laminated fine- to coarse-grained sandstone</td>
<td>Migration of lower flow regime current ripples (unidirectional or bidirectional).</td>
</tr>
<tr>
<td>Sh</td>
<td>Horizontally laminated sandstone</td>
<td>Upper flow regime plane bed migration.</td>
</tr>
<tr>
<td>St</td>
<td>Trough cross-stratified fine- to very coarse sandstone</td>
<td>Lower flow regime migration of 3-D dunes.</td>
</tr>
<tr>
<td>Sm</td>
<td>Massive fine- to very coarse-grained sandstone</td>
<td>Original depositional process unknown due to destruction of primary sedimentary structures.</td>
</tr>
<tr>
<td>P</td>
<td>Paleosol</td>
<td>Pedogenic alteration of post-depositional mudrock and sandstone by eluviation, illuviation, roots, and bioturbation.</td>
</tr>
</tbody>
</table>
and appear laterally continuous over 100s of meters. Black and brown shale strata often exude a musty, organic aroma.

Shale and carbonate mudstone strata frequently interbed with tabular 0.4-1.2 m vertical sequences of normally graded very fine sandstone to siltstone. Vertical sequences consist of: 1) a planar non- to weakly-erosive basal contact; 2) horizontally-laminated very fine sandstone with rare 0.05-0.3m convolute bedding; and 3) ripple cross-laminated very fine sandstone and siltstone. At one location, basal sandstone beds contain mudrock intraclasts.

Offshore lacustrine facies (FA1) rocks infrequently occur within the basin. Where present, FA1 strata outcrop within the basal half of a given El Molino Formation stratigraphic section. The greatest concentration of FA1 strata occurs at the Ichilula and Maragua localities with subordinate outcroppings at Challa Mayu, Vilcapuyo and Camargo (Fig. 3-6). FA1 stratigraphic packages rarely reach thickness greater than 7m and pass from or into FA2 nearshore facies strata.

3.2.1.2 Interpretation

Thin, flat lamination suggests deposition of clastic and carbonate mud by suspension settling (Zhang et al. 1998). Carbonate material is derived from three possible sources: 1) primary inorganic precipitation of CaCO₃; 2) biogenically-produced CaCO₃ shells or structural components; and 3) allochthonous carbonate clasts derived from the drainage basin or cannibalized from carbonate deposits within the depositional basin (Kelts and Hsu 1978; Dean and Fouch 1983; Eugster and Kelts 1983). Carbonate material derived from source (3) requires the erosion and transportation of drainage system carbonate rocks (Kelts and Hsu 1978). While potential carbonate source rocks existed
Figure 3-6. Regional distribution of FA1: Open water facies association.
within the depositional basin (e.g., Permo-Carboniferous Copacabana Formation), the paucity of marlstone beds suggests that chemically precipitated and/or microfossil-derived material dominated carbonate mud input. Chemically precipitated and microfossil-derived carbonate sediment requires quiet water depositional conditions devoid of significant clastic input (Tucker and Wright 1995).

Interstratified shale and laminated carbonate mudstone commonly represent lacustrine deposition (Eugster and Kelts 1983). The irregular stacking distribution of siliciclastic and carbonate laminae, and the dominance of siliciclastic laminae in FA1, suggest long-term variability in sedimentation rather than seasonal variability. Since siliciclastic input dilutes carbonate sedimentation (Tucker and Wright 1995), carbonate production likely occurred during highstands when the depositional area was far from inflow point sources. Laminae preservation suggests deposition within an environment prohibitive to bioturbation, pedogenesis, intra-sediment growth of saline minerals or other processes capable of destroying primary sedimentary structures. Depositional environments that meet this criteria include: 1) shallow, hypersaline lakes; and 2) anoxic bottom water conditions (Hsu and Kelt 1978; Shinn 1983; Soreghan 1998; Del Papa 1999; Lukasik 2000). The absence of mud cracks, evaporite accumulations and red, oxidized strata excludes a shallow, hypersaline lake interpretation. The black, gray, brown and green coloration and organic aroma of shale strata suggests deposition within an anoxic environment.

Very fine-grained 0.4-1.2 m thick sandstone and siltstone beds in FA1 represent intermittent increases in the energy available for sediment transport. Planar basal contacts and rare intraclasts in overlying sandstones indicate deposition by non-erosive to weakly
erosive processes. Horizontal lamination indicates bedload transport in plane beds while overlying ripple cross-laminated strata represent mixed bedload and suspended load transport in current ripples. The sedimentary structures and grain-size distribution of these beds suggests deposition during fine-grained storm events or low-density turbidity flows (Middleton and Hampton 1976; Cheel and Leckie 1992). Storm events introduce coarser-grained sediment into fine-grained open water environments by lowering wave base and thereby increasing the energy available for offshore sediment transport at a given depth. Fine-grained storm bed strata ideally consist of an erosive basal contact that may exhibit sole marks followed by deposition of intraclast-rich horizontally-laminated sandstone, an overlying hummocky cross-stratified layer and cap of ripple cross-stratified sediment (Cheel and Leckie 1992). Turbidity flows can represent the remobilization of basin margin deposits triggered by a destabilizing event and transported basinward by turbulent flow (Boggs 1995). Low-density turbidity flows ideally include the following sequence of sedimentary structures: 1) an erosive base containing flute casts and tool marks; 2) horizontally-laminated sandstone; 3) small-scale cross-bedded sandstone or siltstone; 4) ripple cross-stratified sandstone or mudrock (Middleton and Hampton 1976). Sedimentary structures and grain-size distributions present in FA1 sandstone and siltstone rocks are consistent with either interpretation.

In conclusion, an anoxic to low oxygen depositional interpretation within a meromictic lacustrine environment for FA1 strata is supported by the following observations: 1) interstratified black, brown and green shale and laminated carbonate mudstone; 2) the lack of body or trace fossils; and 3) absence of evaporitic minerals and/or mud cracks.
3.2.2 FA2: Nearshore Facies

3.2.2.1 Description

The nearshore facies (Fig. 3-7) consists of intercalated carbonate and clastic strata. Carbonate strata include 0.05-1.2m thick massive, yellow to gray mudstone and wackestone beds with polygonal mud cracks (Fig. 3-8), horizontal trace fossils, rare dinosaur trackways (Fig. 3-9) and chert nodules. Wackestone beds contain articulated gastropod and bivalve body fossils, casts and molds. Opaline or sparry minerals commonly replace gastropod body fossils.

Low relief, smooth 0.1-0.5m stromatolite boundstone strata (Fig. 3-10) commonly occur within or cap massive carbonate mudstone units. Rare mammilated stromatolite boundstone beds occur at the Challa Mayu locality where bed thickness ranges from 0.1-0.3m. Low relief, smooth stromatolite boundstone beds are laterally extensive for 10’s of meters while mammilated stromatolite boundstone rocks extend laterally for 1-3m before passing into carbonate or clastic rocks.

Clastic strata consist of red to reddish purple, 0.1-40m thick, massive mudstones and 0.1-25m thick horizontally-laminated and ripple cross-laminated mudstones and siltstones. Calcareous, clayey mudstone beds contain symmetrical or nearly symmetrical map view ripples that commonly cap carbonate rocks. In addition, mudstone and siltstone beds include mud cracks and vertical, horizontal and cruciform trace fossils.

FA2 rocks represent the dominant facies association in the study area (Fig. 3-11), reaching continuous stratigraphic thickness greater than120m (e.g., El Puente, Appendix 1) and comprising >80% of a given section. FA2 rocks pass into FA1, FA3 or, more rarely FA4 rocks.
Figure 3-7. Graphic representation of FA2: Nearshore lacustrine facies association. Lithologic codes and legend show in Figure 3-5 and Table 3-1.
Figure 3-8. Mud cracks present in the top of a massive limestone bed from facies association 2: Nearshore facies. Photograph is from the Maragua section.
Figure 3-9. Photograph showing a theropod trackway in El Molino Formation FA2 rocks near Sucre. The theropod trackway is bracketed by the dashed blue lines.
Figure 3-10. Mammilated stromatolites within FA2 nearshore facies strata at Challa Mayu.
Figure 3-11. Geographic distribution of FA2 nearshore lacustrine facies.
3.2.2.2 Interpretation

Massive carbonate sediment accumulation in FA2 strata results from the chemical precipitation of carbonate material and/or suspension fallout of biotic shells and biogenic structural parts. Carbonate wackestone beds indicate deposition within relatively quiet waters that lacked sufficient energy to winnow out carbonate mud material. Preservation of articulated gastropod and bivalve material within these beds suggests minimal transport and erosion indicating low energy deposition, probably in or very near the oxygenated, shallow nearshore life environment of the fauna (Surdam and Stanley 1979; Fouch and Dean 1982; Pratt and James 1986; Castle 1990; Soreghan 1998).

Stromatolitic boundstone beds represent the preserved remains of microbial algal mats and trapped sediment (Pratt and James 1986; Tucker and Wright 1990). The primary control on stromatolite development is invertebrate grazing (Kendall and Skipwith 1968; Playford and Cockbain 1976). Conditions prohibitive to invertebrate grazing include hypersaline conditions and sites prone to subaerial exposure (Birke 1974; Playford and Cockbain 1976). Although stromatolites can exist at depths greater than 60m (Gow 1981), flat, smooth stromatolites commonly occupy stable, shallow (>12m) low-energy shorelines while more highly ornamented (e.g., mammilated) stromatolites exist between –2 to 0m along higher energy shorelines (Hoffman 1976; Casanova 1986).

Laminated, ripple cross-laminated and massive mudstones and siltstones represent sediment deposition by suspension fallout and the migration of current ripples during bedload transport. The presence of mud cracks within these strata suggests periodic subaerial exposure. While desiccation processes during intervals of subaerial exposure produce mud cracks, mud cracks also result from subaqueous shrinkage processes.
(synaeresis cracks) and syndepositional burial stress (diastasis cracks), making an interpretation for periodic subaerial exposure based just on mud cracks somewhat tenuous (Donovan and Foster 1972; Cowan and James 1992; Paik and Kim 1998). However, the association of these rocks with FA4 floodplain facies strata (discussed below), and the rarity of subaqueous shrinkage cracks (Astin and Rogers 1991) and documented diastasis cracks supports an interpretation for episodic subaerial exposure.

Destruction of primary sedimentary structures in massive clastic and carbonate beds results from bioturbation, mud-cracking, intra-sediment growth of saline minerals and/or pedogenesis (Eugster and Kelts 1983; Smoot and Castens-Seidell 1983; Platt 1989). Destruction of FA2 primary sedimentary structures probably resulted from a combination of two processes: 1) bioturbation; and 2) mud-cracking. Numerous horizontal and vertical trace fossils present in siliciclastic and carbonate strata indicate the presence of burrowing fauna capable of disrupting primary sedimentary structures. Abundant mud cracks preserved in massive FA2 rocks and in juxtaposed laminated and ripple cross-laminated mudrocks suggest depositional conditions amenable to mud crack development. Although the destruction of FA2 primary sedimentary structures by the growth of intra-sediment saline minerals or pedogenesis remains a possible mechanism for sediment homogenization, evaporite minerals and/or evaporite mineral casts as well as pedogenic features such as hackly texture, mottling, root traces, distinct color or textural horizons and nodular carbonate accumulations (Retallack 1988; Kraus and Aslan 1999; Mack et al. 2000) are absent.

In summary, FA2 strata are interpreted as low energy, nearshore deposits based on the presence of: 1) thick, massive carbonate mudstone and wackestone deposits; 2)
articulated bivalve and gastropod fossils; 3) ubiquitous low relief, flat stromatolites; and 4) desiccation mud cracks.

3.2.3 FA3 Beach, Bar and Shoal Facies

3.2.3.1 Description:

FA3 strata (Fig. 3-12) consist of 0.01-4.3m peloidal, oolitic, fossiliferous and quartzose packstone, grainstone and very fine- to coarse-grained sandstone beds. These rocks contain concave-up or planar basal contacts, trough cross-bedding, horizontal lamination and massive sedimentary structures (Figs. 3-13, 3-14). Less commonly the packstone, grainstone and sandstone units contain ripple cross-stratified caps. In rare instances, trough cross-bedded or horizontally-laminated packstone, grainstone and sandstone beds contain carbonate or mud intraclasts. Fossil material consists of < 0.01m unidentifiable shell fragments and/or 0.01-0.04 m large bivalve fragments. Opal or sparite commonly replaces original fossil matter. Packstone and grainstone beds commonly consist of very well-sorted peloids or ooids. More rarely, peloidal and oolitic packstone and grainstone beds will contain sand-sized clastic material and fossil fragments. Thin 0.01-0.15m thick grainstone and packstone beds commonly cap stromatolitic boundstones. Sandstone strata range from poorly-sorted sandstones containing angular ostracod, unidentified fossil, peloidal, oolitic and clastic fragments to quartz-rich, well-rounded, very well-sorted sandstones. Additionally, fish bone fragments occur in poorly-sorted sandstones from Vilcapuyo while pebble-sized clasts are present in several Vila Vila and Incapampa sandstone beds. At Incapampa, articulated silica-replaced gastropod body fossils are present within moderate- to well-sorted sandstone beds. Vertical and
Figure 3-12. Graphic representation of FA3 beach, bar and shoal facies association. Lithofacies codes and legend are shown in Figure 3-5 and Table 3-1.
Figure 3-13. Horizontally-laminated and low angle trough cross-stratified peloidal sandstone within FA3 beach, bar and shoal facies at Torotoro.
Figure 3-14. Fossiliferous packstone present in El Molino Formation FA3 beach, bar and shoal facies strata at Challa Mayu.
cruciform trace fossils occur within massive sandstones at Incapampa, Vila Vila and Suticolla.

Figure 3-15 shows the distribution of FA3 packstone, grainstone and sandstone beds. The greatest thickness of FA3 strata occurs in stratigraphic sections along the eastern boundary of the area of investigation (Torotoro, Vila Vila, Incapampa, Camargo and El Puente sections; see Appendix 1). Beds of 1-4.3m thick oolitic and peloidal grainstones and packstones dominate FA3 rocks at Torotoro, El Puente and Camargo while sections further east consist largely of sandstone beds. FA3 rocks from the eastern boundary of the area of interest grade upwards into FA4 and FA5 strata. Although FA3 strata appear broadly distributed, most FA3 occurrences consist of 0.01-0.15m thick grainstone and packstone beds that cap FA2 carbonate mudstone, wackestone and stromatolitic boundstone beds.

3.2.3.2 Interpretation

Ooid and peloid formation can occur in pedogenic, fluvial, cave, lagoonal, shallow marine and lacustrine environments (Tucker and Wright 1990), however, ooids are most commonly known from agitated shallow marine (e.g., Bahama Banks; Cambrian Port au Port Group) and saline lacustrine waters (e.g., Great Salt Lake; Green River Formation) (Eugster and Hardie 1975; Hardie et al. 1978; Surdam and Stanley 1979; Dean and Fouch 1983; Eugster and Kelts 1983; Smoot 1983; Pratt and James 1986; Chow and James 1987; Castle 1990). The association of these rocks with gastropod, bivalve and fish fossils and fragments suggests a lagoonal, shallow marine or saline lacustrine setting for El Molino Formation ooids and peloids. Trough cross-bedded and horizontally-laminated, peloidal and oolitic packstone, grainstone and sandstone beds
Figure 3-15. Regional distribution of FA3: beach, bar and shoal facies association. Although FA3 strata appear to have significant geographic distribution, primary FA3 facies concentrations occur in El Puente, Camargo, Incapampa and Vila Vila. Other Fa3 sites largely consist of thin (< 0.3 m) peloidal or fossiliferous beds interbedded with FA2 strata.
suggest bedload transportation in lower flow regime 3-D dunes or upper flow regime plane beds (Soreghan 1998). Concave-up basal contacts and associated intraclasts represent erosional processes during bed migration. Similar processes likely governed deposition of massive, well-sorted packstone, grainstone and sandstone beds but grain-size homogeneity may have masked associated sedimentary structures. Rocks characterized by good sorting, coarse grain size, abundance of peloids/ooids and an absence of mud matrix suggest continuous reworking by wave action (Castle 1990; Soreghan 1998; Lukasik 2000), precluding deposition within lagoonal conditions.

In contrast, poorly sorted rocks with angular and sub-angular clasts and easily eroded fossil fragments did not undergo continuous reworking by wave action. Instead, the sand-sized sediment fraction likely represents intervals of rapid, high-energy deposition while finer-grained material accumulated under relatively quiet water conditions. Poorly sorted rocks are interpreted as backshore washover deposits.

FA3 sandstone, packstone and grainstone beds are interpreted as beach, bar or shoal deposits. This interpretation is based on a combination of the following evidence: 1) sediment grain size; 2) sedimentary structures indicative of traction transport; 3) presence of gastropod, bivalve, fish bones and unidentifiable fossil material; 4) calcareous nature of sediments; and 5) presence of ooids and peloids.

3.2.4 FA4: Floodplain Facies

3.2.4.1 Description

FA4 facies rocks (Fig. 3-16) consist of 0.4-30 m thick laminated and massive red to reddish-brown mudstone and siltstone beds and 3-9.5 m thick massive medium- to coarse-grained sandstone beds. Mudstone and siltstone strata contain infrequent ripple
Figure 3-16. Graphic representation of FA4 floodplain facies association. Figure 3-5 and Table 3-1 show lithofacies legend and facies codes used in this figure.
cross-lamination, uncommon trace fossils and mud cracks. More rarely, massive mudstone and siltstone beds include hackly texture, mottling, root casts, distinct lateral horizons (Fig. 3-17) characterized by color and/or texture and carbonate accumulations that consist of extremely calcareous matrix material and/or 0.05-0.2m diameter amalgamated carbonate nodules (Fig. 3-18). Of these features, carbonate accumulation is most common, forming 0.1-1.5m thick carbonate-rich horizons with gradational lower contacts and mildly gradational to abrupt upper contacts.

The only outcrops of FA4 facies sandstone occur at Incapampa where massive sandstone beds contain significant carbonate matrix accumulations and carbonate nodules. Carbonate nodules range in size from <0.01 to 0.08 m and commonly form irregular sub-vertical columns. These columns occasionally amalgamate into <1m thick horizons with gradational or abrupt contacts.

FA4 massive sandstones occur between FA3 strata and FA5 strata. FA4 strata interbed with FA2, FA3 and FA5 strata and typically outcrop in the upper half or third of a given El Molino Formation stratigraphic section. FA4 strata were present at all measured sections excluding those at the Challa Mayu, Vilcapuyo and El Puente localities. Figure 3-19 shows the geographic distribution of FA4 strata.

3.2.4.2 Interpretation

Laminated and massive mudstone and siltstone beds represent sediment deposited during suspension fallout and current migration (Zhang et al. 1998), and are interpreted as floodplain deposits. Sediment homogenization by bioturbation, desiccation processes and/or pedogenesis act to destroy primary sedimentary structures within massive mudstone and siltstone strata (Eugster and Kelts 1983; Smoot and Castens-Seidell 1983;
Figure 3-17. El Molino Formation FA4 floodplain facies strata at Incapampa displaying horizontal banding commonly associated with pedogenesis. Soil horizon bands are further emphasized by blue dashed lines. Person is ~ 1.8 m tall.
Figure 3-18. Photograph of amalgamated carbonate nodules within FA4 floodplain facies massive sandstone at Incapampa.
Figure 3-19. Regional distribution of FA4 floodplain facies association strata. Note that facies distribution shows broad depositional extent but main FA4 facies concentrations occur at Jesus de Machaca, Caluyo, Chuvata and Incapampa.
Destruction of primary sedimentary structures by bioturbation is supported by the presence of rare trace fossils and root traces. Sediment homogenization by desiccation processes is indicated by mud cracks. Evidence for pedogenesis includes hackly texture, mottling, root traces, distinct color and/or textural horizons and carbonate accumulations (Retallack 1988; Kraus and Aslan 1999; Mack et al. 2000). Although not prevalent in FA4 rocks, hackly texture is interpreted as remnant soil structure resulting from repeated shrinking and swelling of soil clays while mottling results from reduction/oxidation reactions during soil formation (Fanning and Fanning 1989). Color and/or textural horizons represent zones of soil eluviation and illuviation.

Carbonate nodules and amalgamated nodule accumulations within massive mudstone, siltstone and sandstone strata are interpreted as zones of carbonate illuviation (Bk horizon) within relict soils. Authigenic carbonate forms in pedogenic environments, at or near the water table, near springs or in zones of shallow infiltration and runoff (Mack et al. 2000). These authors provide the following criteria for distinguishing pedogenic carbonate from other forms of authigenic carbonate: 1) presence of well-developed paleosol horizons; 2) gradational or erosional upper contact and gradational lower contact; and 3) vertical orientation of carbonate accumulations. Carbonate nodules and accumulations in FA4 meet criteria (2) and (3), supporting a pedogenic origin. Pedogenic carbonate accumulations commonly form in arid to sub-humid climates where precipitation <100 cm/year (Cerling 1984; Cerling and Quade 1993; Pendall et al. 1994; Mack et al. 2000).

While paleosols commonly occur in floodplain environments, laminated mudstone and siltstone as well as massive mudstone, siltstone and sandstone strata
support interpretations for several additional depositional settings. In order to
differentiate FA4 strata from FA2, FA3 or FA5 rocks, the following generalizations were
made. FA4 floodplain rocks interbedded with FA2 nearshore or FA3 beach, bar and shoal
strata were distinguished exclusively by the presence of pedogenic features. Pedogenic
features were also used to differentiate between FA4 and FA5 massive sandstone beds.
Lastly, laminated and massive mudstone and siltstone associated with FA5 fluvial facies
deposits were interpreted as FA4 floodplain strata with or without evidence for
pedogenesis.

3.2.5 FA5: Fluvial Facies

3.2.5.1 Description

The fluvial facies (Fig. 3-20) consist of 0.1-12 m thick, laterally extensive
(>60m), very fine- to coarse-grained, trough cross-stratified, horizontally-laminated,
ripple cross-laminated and massive sandstone beds. FA5 sandstone strata can be divided
into two subsets based on sand body geometry and the nature of the basal contact: 1)
horizontally-laminated and trough cross-bedded fine- to coarse-grained sandstone beds
with lenticular sand body geometry and sharp, erosive basal contacts (Fig. 3-21); or 2)
horizontally-laminated, trough cross-stratified or ripple cross-laminated, very fine- to
medium-grained sandstone units with tabular sand body geometry and weakly- to non-
erosive basal contacts (Fig. 3-22).

Lens-shaped sandstone beds form 3-12 m thick, stacked multistory sand bodies.
Occasionally, laminated or massive 0.02-0.2 m thick mudstone and siltstone beds drape
sandstone bedsets. Many trough cross-beds contain granule- to pebble-sized mudstone
intraclasts that delineate the lower bounding surface. Individual sandstone beds display
Figure 3-20. Graphic representation of FA5 fluvial facies association. Figure 3-5 and Table 3-1 show lithology legends and facies codes.
Figure 3-21. Lenticular sandstone bed from FA5 fluvial facies at Incapampa. Note the erosional, concave up sandstone base truncating underlying mudrock. Jacob staff is 1.6 m tall.
Figure 3-22. Horizontally-laminated sandstone within an FA5 fluvial facies tabular sandstone.
normal grading or lack grading while grain-size at the bedset scale may vary considerably. At the composite bedset scale, grain-size commonly fines upward as poorly- to moderately-sorted, 0.1-0.6 m thick trough cross-beds are replaced by moderately- to well-sorted, horizontally-laminated and ripple cross-laminated strata.

Tabular sand bodies consist of 0.1-3.5 m thick sand bodies, dominated by horizontally-laminated strata with rare trough cross-beds and/or ripple cross-laminated caps. Less frequently, tabular sandstone beds show massive sedimentary structures that typically cap sandstone beds. Tabular sand bodies display normal grading and consist of moderately- to well-sorted sediment. FA4 floodplain facies strata bracket tabular sandstone beds.

Where present, fluvial facies strata occupy the upper half to third of El Molino Formation strata and interbed with FA4 floodplain facies strata. While individual sand bodies typically fine upwards, grain size actually increases up stratigraphic section. FA5 sandstone units outcrop at Jesus de Machaca, Caluyo, Chuvata and Incapampa (Fig. 3-23).

3.2.5.2 Interpretation

FA5 horizontally-laminated, trough cross-stratified and ripple cross-laminated sandstone beds represent deposition by traction currents. Horizontally-laminated sandstone beds represent sediment transported within plane beds while trough cross-stratified and ripple cross-laminated sandstone strata indicate the migration of lower flow regime dunes and current ripples (Miall 1978).

Multi-story, stacked, lenticular-shaped sand bodies are interpreted as fluvial channel sandstone beds. The presence of abundant mudstone intraclasts within trough
Figure 3-23. Regional distribution of FA5 fluvial facies association strata.
cross-beds suggests the erosion and reworking of muddy sediments within or adjacent to the fluvial channel (Cant 1982). Grain-size variation and the draping of trough cross-beds by mudstone or siltstone indicate inconsistent channel flow velocities and potentially represent brief periods of channel abandonment and subaerial exposure. Fining upward grain-size trends and bedform transitions from horizontally-laminated to ripple cross-laminated sandstone beds suggest an overall reduction in flow velocity and the progressive abandonment of the fluvial channel (Miall 1978, 1996).

Sandstone strata showing tabular geometry and non- to weakly-erosive basal bounding surfaces are interpreted as unconfined sheet flood beds. The absence or near absence of erosive bounding surfaces suggests rapid dissipation of flow energy. Decreasing flow energy is also suggested by bedform transitions from horizontally-laminated beds and rare trough cross beds to ripple cross-laminated strata (Miall 1978, 1996). The prevalence of massive sandstone structure at the top of these sand bodies may have resulted from post-depositional pedogenesis, desiccation processes or bioturbation (Eugster and Kelts 1983; Smoot and Castens-Seidell 1983; Platt 1989).

The increase in sandstone outcrop frequency and upward increase in grain-size suggests increased fluvial flow energy and/or reduced transport distance from drainage basin source rocks.

3.3 Discussion

The El Molino Formation consists of open water (FA1), nearshore (FA2), beach, bar and shoal (FA3), floodplain (FA4) and fluvial (FA5) facies strata. These strata are interpreted as deposits within a dynamic, dominantly lacustrine depositional system with basin margin fluvial/floodplain strata becoming important towards the end of El Molino
Formation deposition. The majority of lacustrine deposition occurred under hydrologically-closed basin conditions. Hydrologically-closed lacustrine basins are characterized by rapid and frequent facies shifts and the presence of evaporites (Hardie et al. 1978; Eugster and Kelts 1983). While determining the actual timing of El Molino Formation facies shifts is impossible with the given data, an inference supporting rapid and frequent facies changes can be made based on the frequency of lithofacies variation within a given stratigraphic section. In addition, the presence of mud cracks within FA2 nearshore facies deposits and FA2 associations with pedogenic features of FA4 floodplain facies strata suggests episodic subaerial exposure of nearshore deposits. Gypsum deposits at Agua Salud also support a hydrologically-closed basin interpretation.

Hydrologically-closed lacustrine settings can be further divided into perennial and ephemeral saline lakes (Eugster and Hardie 1983). Perennial saline lakes (e.g. Great Salt Lake) hold water year round. Alternately, ephemeral saline lakes (e.g. Death Valley) only contain water during periods of increased precipitation and/or reduced evaporation, and are commonly characterized by evaporite accumulations indicative of hypersalinity and evidence for subaerial exposure. Although periodic subaerial exposure of lacustrine strata and limited evaporite deposition is consistent with an ephemeral saline lake environment, the presence of ubiquitous gastropods and bivalves indicates that El Molino Formation lake waters were not hypersaline, instead suggesting a perennial saline lake environment.

The presence of marine fossils indicates that the El Molino Formation was periodically a shallow marine (Gayet et al. 1991, 1993, 2001; Sempere et al. 1997) or an open lacustrine system (Rouchy et al. 1993; Camoin et al. 1997). As suggested by Sempere et al. (1997), a shallow marine depositional environment is circumstantially
supported by contemporaneous global high-stands during deposition of Lower and Upper El Molino Formation carbonates. The Upper Zuni cycle 4.5 and Tejas cycle 1.2 global high-stands occur during deposition of significant lower and upper El Molino Formation carbonate beds attributed to a shallow marine environment (Haq et al. 1987; Sempere et al. 1997). However, the Tejas cycle 1.1 high-stand, which shows a higher amplitude than the Tejas cycle 1.2, corresponds with a phase of mudrock deposition attributed to Middle El Molino Formation non-marine deposition (Haq et al. 1987; Rouchy et al. 1993; Camoin et al. 1997; Sempere et al. 1997). This calls into question the inference relating Upper El Molino Formation deposition to a marine transgression.

The fluvial/floodplain strata present near Lake Titicaca represent Middle to Upper El Molino Formation deposits. The coarsening-upward trend seen in Lake Titicaca deposits suggests progradation of fluvial sediments into the lacustrine system. This trend is more compatible with fluvial inflow into the El Molino Formation depositional basin than outflow. A coarsening-upward trend also occurs at Incapampa where beach, bar and shoal facies are replaced up section by fluvial/floodplain strata, again supporting the progradation of fluvial sediment into the El Molino Formation depositional basin. Based on stratigraphic stacking patterns present at Jesus de Machaca, Caluyo, Chuvata, Incapampa and Vila Vila, the Upper El Molino Formation basin was characterized by progradation of basin perimeter sediments into the basin. This observation makes an Upper El Molino Formation marine transgression unlikely.

The sedimentary facies present in the El Molino Formation provide some evidence for determining tectonic setting. Lacustrine depositional environments exist in syn-rift and post-rift settings as well as foreland basin wedge-top, foredeep and back-
bulge depocenters (Stanley and Collinson 1979; Surdam and Stanley 1979; Sclater and Christie 1980; Ingersoll 1988; Cohen 1990; McHargue et al. 1992; Friedmann and Burbank 1995; DeCelles and Giles 1996; Currie 1998; Crossley and Cripps 1999). The absence of El Molino Formation alluvial fan facies strata and growth strata, indicating syndepositional normal or thrust faulting, eliminates syn-rift or foreland basin wedge-top depositional environments. Remaining depositional environments include foreland basin foredeep and back-bulge depocenters in addition to post-rift settings.
4. PALEOCURRENT DIRECTIONS AND PROVENANCE

4.1 Methods and Background Data

Paleocurrent directions were measured and calculated for nineteen stations from four measured stratigraphic section localities. Data include 185 measurements taken from sandstone trough cross-bed axes and trough cross-bed limbs. Paleocurrent direction for trough cross-bedded sandstone limbs was calculated using DeCelles et al. (1983) method I. Paleocurrent direction determination using DeCelles et al. (1983) method I is accomplished by measuring the strike and dip of trough cross-bed 3-D limb exposures. Trough cross-bed limb measurements are divided into right and left hand populations based on their relative orientation and subsequently plotted as poles on a stereographic Schmidt Net. An average point is selected from each population and subsequently fitted to a great circle. The pole to that great circle represents the trend and plunge of the average trough axis for an outcrop which can be used as a paleocurrent direction indicator once corrected for stratigraphic strike and dip (DeCelles et al. 1983).

Twenty-three sandstone thin-section samples and eight clast counts were collected from medium-grained to pebbly sandstones for provenance analysis. Due to the limited distribution of sandstone strata throughout the El Molino Formation depositional system, sandstone provenance data were only collected from the Incapampa, Jesus de Machaca, Suticolla, Vila Vila and Vilcapuyo stratigraphic sections. Sandstone samples collected from Vilcapuyo show clast compositions consisting of >80% autochthonous oolitic, peloidal and fossil fragment material and, therefore, were not used for subsequent provenance studies.
Sandstone thin-section samples were stained for calcium and alkali feldspars using the procedure of Houghton (1980). At least 400 grains were identified from each thin-section following the Gazzi-Dickinson method (Dickinson 1970; Ingersoll et al. 1984). The Gazzi-Dickinson method of thin section point counting is designed to maximize source rock data important to tectonic investigations. For this purpose, sand-sized crystals and grains within larger fragments are counted the same as crystals and grains not included within larger fragments (e.g. a sand-sized quartz crystal within a volcanlastic fragment is counted as a quartz crystal and not as a volcanic lithic fragment). This effectively eliminates compositional variation based on differences in grain size, thereby reducing the effects of transport history on source rock provenance determination (Ingersoll et al. 1984). Table 4-1 summarizes grain parameters and recalculated parameters used during thin-section point-counting and subsequent analyses. Table 4-2 shows raw thin-section point-count data.

Clast counts consist of ~100 clast identifications per count. Clasts counts were conducted by first designating a ~0.5m square box on the outcrop. Lithologies for granule-sized or greater clasts within the box were then identified and marked until the count reached 100. Clast lithologies present in the El Molino Formation include quartz-rich beige sandstones and quartzites, greenish-gray calcium carbonates, dolomitic conglomerates, chert and quartz clasts, and reddish-beige, reddish-purple, alligator green, white, blue-black, brown-black and gray quartzites. Quartz-rich beige sandstones represent Cretaceous La Puerta Formation rocks. La Puerta Formation and equivalent strata display broad distribution throughout the Eastern Cordillera and eastern Altiplano. However, these rocks are absent from the Jesus de Machaca locality, indicating non-
Table 4-1. Table showing parameters and recalculated parameters for thin section point counts using the Gazzi-Dickinson method (modified from Ingersoll et al. 1984).

<table>
<thead>
<tr>
<th>Counted Parameters</th>
<th>Recalculated Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qp = polycrystalline quartz (including chert)</td>
<td>Q = Qp + Qm</td>
</tr>
<tr>
<td>Qm = monocrystalline quartz</td>
<td>F = P + K</td>
</tr>
<tr>
<td>P = plagioclase feldspar</td>
<td>L = Lv + Lm + Ls</td>
</tr>
<tr>
<td>K = potassium feldspar</td>
<td></td>
</tr>
<tr>
<td>Lv = volcanic or hypabyssal lithic fragments</td>
<td></td>
</tr>
<tr>
<td>Lm = metamorphic lithic fragments</td>
<td></td>
</tr>
<tr>
<td>Ls = sedimentary lithic fragments</td>
<td></td>
</tr>
<tr>
<td>M = phyllosilicates</td>
<td></td>
</tr>
<tr>
<td>D = dense minerals</td>
<td></td>
</tr>
<tr>
<td>Misc. = miscellaneous and unidentified</td>
<td></td>
</tr>
</tbody>
</table>
Table 4-2. Raw point count data used in provenance analysis and in related figures. Sample name prefixes indicate sample locality as follows: JM = Jesus de Machaca; SU = Suticolla; and IN = Incapampa. Middle code indicates formation name: EM = El Molino.

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Qm</th>
<th>Qp</th>
<th>Q</th>
<th>P</th>
<th>K</th>
<th>F</th>
<th>Lv</th>
<th>Ls</th>
<th>Lm</th>
<th>L</th>
<th>M</th>
<th>D</th>
<th>AA</th>
</tr>
</thead>
<tbody>
<tr>
<td>JM-2</td>
<td>225</td>
<td>5</td>
<td>230</td>
<td>129</td>
<td>23</td>
<td>152</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JM-4</td>
<td>268</td>
<td>8</td>
<td>276</td>
<td>112</td>
<td>4</td>
<td>116</td>
<td>8</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JM-5</td>
<td>160</td>
<td>23</td>
<td>183</td>
<td>155</td>
<td>40</td>
<td>195</td>
<td>2</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JM-6</td>
<td>193</td>
<td>10</td>
<td>203</td>
<td>165</td>
<td>26</td>
<td>191</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JM-7</td>
<td>191</td>
<td>14</td>
<td>205</td>
<td>171</td>
<td>20</td>
<td>191</td>
<td>4</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JM-8</td>
<td>178</td>
<td>16</td>
<td>194</td>
<td>160</td>
<td>37</td>
<td>197</td>
<td>5</td>
<td></td>
<td>5</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JM-9</td>
<td>240</td>
<td>23</td>
<td>263</td>
<td>107</td>
<td>23</td>
<td>130</td>
<td>4</td>
<td></td>
<td>4</td>
<td>1</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JM-10</td>
<td>225</td>
<td>37</td>
<td>262</td>
<td>71</td>
<td>64</td>
<td>135</td>
<td>1</td>
<td></td>
<td>1</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SU-EM-02</td>
<td>323</td>
<td>20</td>
<td>343</td>
<td>35</td>
<td>15</td>
<td>50</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SU-EM-15</td>
<td>374</td>
<td>7</td>
<td>381</td>
<td>8</td>
<td>2</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SU-EM-48</td>
<td>338</td>
<td>17</td>
<td>355</td>
<td>35</td>
<td>6</td>
<td>41</td>
<td></td>
<td>2</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SU-EM-79</td>
<td>321</td>
<td>15</td>
<td>336</td>
<td>60</td>
<td>2</td>
<td>62</td>
<td>1</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SU-EM-98</td>
<td>376</td>
<td>12</td>
<td>388</td>
<td>7</td>
<td>2</td>
<td>9</td>
<td>1</td>
<td>1</td>
<td></td>
<td>3</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IN-EM-162</td>
<td>257</td>
<td>136</td>
<td>393</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IN-EM-170</td>
<td>358</td>
<td>19</td>
<td>377</td>
<td>20</td>
<td>3</td>
<td>23</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IN-EM-270</td>
<td>331</td>
<td>49</td>
<td>380</td>
<td>15</td>
<td>4</td>
<td>19</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>IN-EM-325</td>
<td>317</td>
<td>66</td>
<td>383</td>
<td>4</td>
<td>13</td>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
deposition or deposition and subsequent erosion prior to El Molino Formation deposition. Greenish-gray calcium carbonate clasts appear identical to CaCO₃ nodules present within underlying, pedogenically-modified La Puerta Formation rocks. Although an exact identification of dolomitic conglomerate clasts cannot be made since no known conglomerate underlying the El Molino Formation contains dolomite, the best interpretation places these clasts within the basal La Puerta Formation. Basal La Puerta Formation strata include conglomeratic beds in several locations and overlie Permo-Carboniferous carbonates. Quartz clasts represent vein quartz present within igneous intrusions and flows associated with the La Puerta Formation. Both clast count localities contain igneous intrusions and/or flows within underlying La Puerta Formation strata. Permo-Carboniferous carbonates represent the likely source for chert clasts (Horton et al. 2001b; Sempere et al. 2002) while reddish-beige, reddish-purple, alligator green, white, blue-black, brown-black and gray quartzites represent Paleozoic strata. Table 4-3 summarizes lithologies present within El Molino Formation strata with associated raw clast count data.

4.2 Description

A regional overview of detrital composition shows diminishing amounts of feldspar from north to south. The Jesus de Machaca section displays the highest feldspar content of the three thin-section sample localities while Incapampa shows the lowest feldspar content (Figs. 4-1, 4-2). Feldspar from El Molino Formation sandstone samples consists primarily of plagioclase. Northwest- and north-derived sandstones from the Jesus de Machaca section (Fig. 4-1) show quartzo-feldspathic composition (Fig. 4-2). Monocrystalline quartz (Qₘ) dominates the quartz (Q) fraction while plagioclase (P)
Table 4-3. Raw El Molino and La Puerta Formation clast count data. Numbers next to locality refers to stratigraphic level where El Molino Formation base equals 0 m. Negative numbers represent La Puerta Formation rocks underlying El Molino Formation strata.

<table>
<thead>
<tr>
<th>Clast Type</th>
<th>Vila Vila 30m</th>
<th>Vila Vila 50m</th>
<th>Vila Vila 90m</th>
<th>Incapampa -50m</th>
<th>Incapampa -28m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beige SS/Quartzite, Cretaceous? La Puerta Fm</td>
<td>96</td>
<td>86</td>
<td>7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CaCO3 nodules, Cretaceous? La Puerta Fm</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Dolomitic Conglomerate, Cretaceous? La Puerta Fm</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Vein Quartz, Cretaceous? Igneous Flows and Intrusions</td>
<td>1</td>
<td>2</td>
<td>29</td>
<td>93</td>
<td>92</td>
</tr>
<tr>
<td>Chert, Permo-Carboniferous</td>
<td>2</td>
<td>0</td>
<td>11</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ordovician to Silurian Quartzites</td>
<td>1</td>
<td>12</td>
<td>54</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100</strong></td>
<td><strong>100</strong></td>
<td><strong>101</strong></td>
<td><strong>100</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Clast Type</th>
<th>Incapampa -24m</th>
<th>Incapampa 12.8 m</th>
<th>Incapampa 197m</th>
<th>Incapampa 280m</th>
<th>Incapampa 290m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beige SS/Quartzite, Cretaceous? La Puerta Fm</td>
<td>0</td>
<td>67</td>
<td>71</td>
<td>7</td>
<td>23</td>
</tr>
<tr>
<td>CaCO3 nodules, Cretaceous? La Puerta Fm</td>
<td>0</td>
<td>11</td>
<td>8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Dolomitic Conglomerate, Cretaceous? La Puerta Fm</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Vein Quartz, Cretaceous? Igneous Flows and Intrusions</td>
<td>85</td>
<td>2</td>
<td>2</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>Chert, Permo-Carboniferous</td>
<td>0</td>
<td>20</td>
<td>0</td>
<td>54</td>
<td>60</td>
</tr>
<tr>
<td>Ordovician to Silurian Quartzites</td>
<td>16</td>
<td>2</td>
<td>19</td>
<td>22</td>
<td>19</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>101</strong></td>
<td><strong>100</strong></td>
<td><strong>100</strong></td>
<td><strong>100</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

N = 101
Figure 4-1. Map showing paleocurrent directions and clast count data. Paleocurrent data consist of measurements taken from the axes and limbs of trough cross-bedded sandstone beds. Trough cross-bed paleocurrent data were extracted using the DeCelles et al. (1983) method I. DeCelles et al. (1983) method 1 data were calculated from 20 ± 4 individual measurements subequally divided between right and left hand limbs. Stratigraphic level and number of measurements per station can be found in Appendix 1. Clast count data consists of 100 ±11 counts per outcrop. Clast count meter levels are in reference to the base of the El Molino Formation (i.e. base of El Molino Formation equals 0).
Figure 4-2. Ternary diagrams illustrating the composition of El Molino Formation sandstone beds at Incapampa and Suticolla. Dashed lines delineate the provenance fields discussed in the text. Provenance fields taken from Dickinson (1979). Q = Quartz; Q$_{m}$ = Monocrystalline Quartz; F = Feldspar; L = Total Lithic Fragments; P = Plagioclase; K = Potassium Feldspar.
makes up the bulk of the feldspar fraction (F). Rare lithic fragments (L) consist of sedimentary lithoclasts (L_s). Sandstone samples from lowermost and uppermost Jesus de Machaca El Molino Formation section show a high quartz fraction compared to feldspar while samples from middle section rocks display subequal quartz and feldspar fractions (Fig. 4-2).

Quartzose sandstones (Fig. 4-2) from the Suticolla section exhibit east-northeast to west-southwest paleoflow (Fig. 4-1). Polycrystalline quartz represents < 6% of the total quartz fraction while the proportionally low feldspar fraction consists mostly of plagioclase with very minor potassium feldspar (Fig. 4-2). Lithic grains are insignificant at Suticolla, consisting of < 1% sedimentary lithic clasts (L_s).

Vila Vila pebbly sandstones lacked preserved sedimentary structures necessary for paleocurrent determination. Clast counts from pebbly sandstones indicate initially high Cretaceous(?) La Puerta Formation sandstone and quartzite clast content and gradually transitions to Cretaceous(?) vein quartz, Permo-Carboniferous chert and Paleozoic quartzites (Fig. 4-1).

Further south at Incapampa, clast counts from the La Puerta Formation are dominated by Cretaceous(?) vein quartz with subordinate amounts of Paleozoic quartzites (Fig. 4-1). Unconformably overlying the La Puerta Formation, El Molino Formation clast counts display high initial proportions of La Puerta Formation clasts and passes up section into a Permo-Carboniferous chert-dominated composition. Paleocurrent measurements indicate paleoflow to the northwest and west (Fig. 4-1).

El Molino Formation thin-section samples at Incampampa consist of quartz-dominated sandstones largely composed of monocrystalline quartz (Fig. 4-2).
Polycrystalline quartz grains from the lowermost Incapampa section represent ~35% of the quartz fraction but immediately diminishes to < 18%. Feldspar at Incapampa accounts for < 6% of total grains with plagioclase dominating the feldspar fraction in all but the uppermost sample.

### 4.3 Interpretation

Paleoflow data (Fig. 4-1) differs throughout the basin indicating variable sandstone source areas. However, all sandstone thin-section point counts plot within the continental block provenance field of Dickinson and Suczek (1979). Paleocurrent data at Jesus de Machaca suggests a northern or northwestern sandstone source area. Abundant monocry stalline quartz represents the erosion of Paleozoic quartzites whereas Jesus de Machaca plagioclase suggests the erosion and transport of magmatic arc source rocks. The concentration of increased plagioclase within middle El Molino Formation suggests temporary modifications within the drainage system to include more magmatic arc source rock area.

Paleoflow at Suticolla indicates sandstone source rocks to the northeast and east. The quartzose nature of these rocks suggests erosion of quartz-rich Mesozoic/Paleozoic sedimentary and metasedimentary rocks. Subordinate feldspar may represent recycled detritus present within source rocks or distal detritus from the magmatic arc. The lack of volcanic lithic fragments rules out a proximal igneous source for sandstone feldspar.

Paleocurrent indicators were absent at the Vila Vila locality. However, clast count data (Fig. 4-1) show an unroofing sequence that begins with the erosion of La Puerta Formation strata. Clast count data from higher stratigraphic levels indicates that La Puerta Formation erosion became less important as older Paleozoic strata became
available for erosion and transport. Since Mesozoic and Paleozoic strata underlie El Molino Formation rocks north, south and west of Vila Vila, the clast source area must lie east.

Incapampa paleoflow indicates an eastern or southeastern detrital source area. Clast count data (Fig. 4-1) shows initial erosion of Cretaceous strata and subsequent unroofing of Permo-Carboniferous chert with subordinate Cretaceous and Paleozoic constituents. The dominance of monocrystalline and polycrystalline quartz in thin-section samples is consistent with the interpretation suggested by clast count data.

4.4 Discussion

Limited provenance and paleocurrent data suggest that the El Molino Formation drainage systems flowed towards a central depositional basin. The absence of paleocurrent data for western and southern El Molino Formation rocks allows the possibility of southern or western outlets to the sea. However, the presence of high topography associated with the magmatic arc to the west reduces the probability of a western outlet. Paleocurrent flow toward a central basin supports syn-rift, post-rift and foreland basin depositional settings.

Clast counts from pebbly sandstones deposited within this basin show an uncomplicated top-to-bottom unroofing sequence consistent with erosion by stratigraphic downcutting. This simple unroofing sequence supports deposition within a syn-rift, post-rift or foreland basin tectonic setting. However, deposition within syn-rift and foreland basin settings could only occur during periods of relative tectonic quiescence. The initiation of new syndepositional normal or thrust faulting would disrupt the unroofing sequence by uplifting new strata for erosion and transport. Assuming that syn-rift and
foreland basin foredeep deposits are zones affected by fault activity, clast count data best support deposition within a foreland basin back bulge or post-rift basin.

Thin-section provenance data support syn-rift or post-rift tectonic settings. Dickinson and Suczek (1979) show that sandstone thin-section point counts plotting within continental block provenance reflect sediment from broad uplifted cratonic or locally uplifted normal fault-bounded basement source areas. Quartzose sandstone deposits from Torotoro and Incapampa indicate the presence of quartz-rich source rocks or an extensive, well-developed drainage system. The abundance of quartzose clasts within pebbly sandstone clast counts indicates the presence of quartz-rich source rocks and supports deposition within syn-rift, post-rift and foreland basins.

However, rocks near Lake Titicaca indicate sediment deposition within syn-rift or post-rift basins. South- and southeast-directed paleoflow of plagioclase-laden sediment from Lake Titicaca (Fig. 4-1) suggests erosion and transport of magmatic arc sediment. The presence of magmatic arc sediment argues against deposition within a foreland basin system since the associated fold-thrust belt would bar sediment transport from a western magmatic arc. However, the possibility of foreland basin deposition remains if Central Andean fold-thrust belt development proves to be diachronous. If a fold-thrust belt northwest of the modern Lake Titicaca failed to develop before or during El Molino Formation deposition, the transport of magmatic arc sediment could flow into a foreland basin system from the northwest.

In conclusion, paleocurrent and provenance data suggest deposition during periods of tectonic quiescence. Although deposition within a syn-rift basin or the wedge-top or foredeep depozones of foreland basin systems cannot be excluded, an
interpretation suggesting post-rift thermal sag or back-bulge basin deposition best fits the data presented.
5. CONCLUSIONS

The El Molino Formation represents a complex sequence of carbonates, mudrocks and sandstones that form two lithostratigraphic sequences. The first lithostratigraphic sequence occupies the central Altiplano and western Eastern Cordillera and consists of three members:

- A lower member comprising ~50% of a stratigraphic section that includes carbonates, carbonate sands and mudrocks;
- A mudrock-rich middle member that makes up ~35% of the section; and
- An upper member consisting of carbonate and mudrock.

The second lithostratigraphic sequence dominates El Molino Formation stratigraphy near Lake Titicaca and in the eastern Eastern Cordillera and contains two members:

- A lower member consisting of carbonate sands, carbonates and mudrocks that comprises ~25% of a given stratigraphic section; and
- An upper member containing sandstones and mudrocks that coarsens upward within a given section.

Within these lithostratigraphic sequences, five facies associations have been identified and their geographic distribution mapped (Fig. 5-1):

- An open water facies association (FA1) comprised of shales and carbonate mudstones showing very limited distribution confined to the east-central Altiplano and west-central Eastern Cordillera;
- A nearshore facies association (FA2) containing mudrocks, and massive carbonate mudstones and wackestones that represent the most common facies association present in the El Molino Formation;
**FA1. Description:** Black, gray, brown and green shale and carbonate mudstone laminae. **Interpretation:** Open water facies.

**FA2. Description:** Massive carbonate mudstone and wackestone; stromatolitic boundstones; Massive, horizontally-laminated and ripple cross-laminated mudstone. **Interpretation:** Nearshore facies.

**FA3. Description:** Peloidal, oolitic, fossiliferous and quartzose packstone, grainstone and very fine to coarse-grained sandstone beds; Trough cross-bedded, horizontally laminated and massive sedimentary structures. **Interpretation:** Beach, bar and shoal facies.

**FA4. Description:** Laminated and massive mudstone and medium- to coarse-grained sandstone beds; Massive mudstone and sandstone strata with carbonate nodules, hackly texture, mottling, mud cracks, root casts and distinct horizons characterized by color and/or texture. **Interpretation:** Floodplain facies.

**FA5. Description:** Horizontally-laminated and trough cross-bedded fine- to coarse-grained sandstone beds with sharp, erosive basal contacts and multistory geometry; Horizontally-laminated, trough cross-bedded or ripple cross laminated very fine- to medium- grained sandstone beds with planar basal contacts. **Interpretation:** Fluvial facies.

Figure 5-1. Summary diagram showing the distribution of facies present within the El Molino Formation and briefly describing the lithologies and interpretations for facies association.
• A beach, bar, and shoal facies association (FA3) consisting of peloidal, oolitic, fossiliferous and quartzose grainstones, packstones and sandstones that show broad geographic distribution but are mainly concentrated in the eastern Eastern Cordillera;

• A floodplain facies association (FA4) containing mudrocks and massive sandstones that also show broad geographic distribution but primarily occur near Lake Titicaca and in the eastern Eastern Cordillera; and

• A fluvial facies association (FA5) consisting of sandstones that are limited to sites near Lake Titicaca as well as Suticolla and Incapampa section localities.

The tendency of these facies associations to overlap one another in map view (Fig. 5-1) and to superimpose one another vertically supports an interpretation for El Molino Formation deposition predominantly within a hydrologically-closed lacustrine system. Based on the abundance of fossil material and the paucity of evaporite deposits, perennial lacustrine conditions are favored over an ephemeral lacustrine setting. However, rare evaporite deposits (e.g. Agua Salud) indicate that ephemeral lacustrine conditions periodically existed in some, if not all, parts of the basin. Marine and brackish water fossils collected by previous workers also indicate that the El Molino Formation depositional basin either experienced a shallow marine incursion(s) or was briefly a hydrologically-open brackish-water lacustrine system. Based on comparisons between the global sea level curve, age data and El Molino Formation lithologies, these conditions likely existed during deposition of lithostratigraphic sequences 1 and 2 lower members. Subsequent to these conditions, strata from the lithostratigraphic sequence 2 upper member prograded into the El Molino Formation depositional basin.
With the exception of sediment deposited near Lake Titicaca, these progradational strata show quartz-rich sandstone provenance that probably reflects the erosion and recycling of Cretaceous (?) sandstone and Paleozoic quartzite sediment. Strata near Lake Titicaca show quartzo-feldspathic composition interpreted to represent sediment transport from source areas proximal to magmatic arc rocks. Despite the provenance differences between strata deposited near Lake Titicaca and eastern Eastern Cordillera strata, all sandstone thin section point count data plot within the continental block provenance field of Dickinson (1979) suggesting syn-rift, post-rift thermal sag and foreland basin back-bulge depositional conditions. Clast count data show a relatively simple unroofing sequence indicative of the tectonic quiescence associated with post-rift thermal sag and foreland basin back-bulge settings.

Post-rift thermal sag and/or foreland basin back-bulge tectonic settings, in addition to syn-rift basins, and foreland basin wedge-top and foredeep depozones can all support lacustrine conditions. However, in light of the provenance data and due to the absence of faulting or fault-related growth strata, El Molino Formation strata are interpreted as post-rift thermal sag and/or foreland basin back-bulge deposits.
REFERENCES


DeCelles, P. G. and Giles, K. A., 1996, Foreland basin systems. Basin Research, 8, 105-123.


Smoot, J. P., 1983, Depositional subenvironments in an arid closed basin; the Wilkins Peak Member of the Green River Formation (Eocene), Wyoming, U.S.A. Sedimentology, 30, 801-827.


APPENDIX A: STRATIGRAPHIC SECTIONS

Agua Salud

Caluyo

Camargo
Ichilula
Vilcapuyos
<table>
<thead>
<tr>
<th>Location Name</th>
<th>Coordinates</th>
<th>Location Notes</th>
<th>Stratigraphic Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andamarca</td>
<td>S18°47.413' W067°31.709'</td>
<td></td>
<td>Conformably overlies Chaunaca Fm and underlies Santa Lucia Fm.</td>
</tr>
<tr>
<td>Camargo</td>
<td>S20°43.518' W065°12.605'</td>
<td>Section measured in San Pedro river valley north of distillery.</td>
<td>El Molino Formation overlies Chaupiuno Fm, a ~20m sandstone unit with micrite lenses. Santa Lucia and Impora Fm overlie El Molino</td>
</tr>
<tr>
<td>Challa Mayu</td>
<td>S19°10.94' W066°06.233'</td>
<td>2km NW of Challa Mayu. Measured in quebrada by sharp 90° turn in Challapatapotosi road.</td>
<td>El Molino overlies Chaunaca Fm and underlies Santa Lucia Fm.</td>
</tr>
<tr>
<td>Chuvata</td>
<td>S16°35.353' W068°59.058'</td>
<td>East of Desaguadero. Measured near the pueblo Asfranal. Indigenous population was extremely suspicious and instructed us to leave. We returned with appropriate paperwork and were allowed to work.</td>
<td>Base of El Molino Fm is truncated by thrust fault. El Molino strata passes upwards into Santa Lucia Fm.</td>
</tr>
<tr>
<td>Location Name</td>
<td>Coordinates</td>
<td>Location Notes</td>
<td>Stratigraphic Notes</td>
</tr>
<tr>
<td>----------------</td>
<td>------------------------------------------</td>
<td>----------------------------------------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>El Puente</td>
<td>S21°14.215' W065°10.788'</td>
<td>Measured section East of the pueblo El Puente starting section east of limestone quarry.</td>
<td>El Molino Fm forms slightly angular unconformity (&lt;10°) with underlying Chaupiuno Fm sandstone. Chaupiuno Fm contains secondary calcareous nodules that may be pedogenic in nature. Santa Lucia Fm overlies El Molino Fm.</td>
</tr>
<tr>
<td>Ichilula</td>
<td>S19°24.312' W067°9.397'</td>
<td>Ichilula is a small pueblo in the northwest Rio Maltos thrust belt between pueblos Chilla Viento and Circoya.</td>
<td>El Molino Fm lies between Chaunaca and Santa Lucia Fm. El Molino and Santa Lucia Fm contact occurs under cover. Upper El Molino and most of the Santa Lucia Fm form a valley around synclinal core.</td>
</tr>
<tr>
<td>Incapampa</td>
<td>S19°27.56' W064°50.58'</td>
<td>Measured section in N. Incapampa syncline along foot path S. of Rio Pilcayo and E. of foot bridge</td>
<td>El Molino Fm unconformably overlies La Puerta Fm. La Puerta Fm. contains numerous calcareous nodules organized into laterally extensive horizons and interpreted as sandy paleosols. El Molino Fm underlies Incapampa Fm possibly suggesting that Santa Lucia Fm rocks were included in El Molino Fm data. However, a facies shift attributable to Santa Lucia deposition was not evident.</td>
</tr>
<tr>
<td>Jesus de Machaca</td>
<td>S16°42.733' W068°46.874'</td>
<td>Began section in drainage NW of small pueblo to N of Jesus de Machaca. Section measured ~E and normal to initial drainage.</td>
<td>Much of this section is obscured by cover. Base of El Molino overlies Paleozoic rocks. El Molino Fm passes upwards into Santa Lucia Fm.</td>
</tr>
</tbody>
</table>
### Stratigraphic Notes

Base of El Molino Fm was under cover but sporadic outcrops and stratigraphy throughout the region suggests that the Chaupiuno and Aroifilla Fms underly El Molino rocks. Santa Lucia strata overlies El Molino Fm, forming a valley within the core of the syncline.

El Molino Fm overlies Chaunaca Fm and underlies Santa Lucia Fm. Rocks at San Pedro de Huallaloco are overturned. Basal stratigraphic relations difficult to discern. Base of El Molino Fm section may include Torotoro rocks. Base of measured section overlies Paleozoic rocks. Santa Lucia Fm overlies El Molino Fm.

### Location Name | Coordinates | Location Notes | Stratigraphic Notes
--- | --- | --- | ---
Maragua | S19°6.378' W065°25.643' | Measured section in valley SW of Irupampa. Indigenous population to SW was hostile, prevented completion of section and would not return our credentials. Locals did not speak Spanish. | Base of El Molino Fm was under cover but sporadic outcrops and stratigraphy throughout the region suggests that the Chaupiuno and Aroifilla Fms underly El Molino rocks. Santa Lucia strata overlies El Molino Fm, forming a valley within the core of the syncline. |
San Pedro de Huallaloco | S18°37.333' W067°35.931' | Measured section immediately N of town. | El Molino Fm overlies Chaunaca Fm and underlies Santa Lucia Fm. Rocks at San Pedro de Huallaloco are overturned. |
Suticolla | | Measured section along La Paz-Cochabamba road W of Suticolla and E of Pongo. | Basal stratigraphic relations difficult to discern. Base of El Molino Fm section may include Torotoro rocks. Base of measured section overlies Paleozoic rocks. Santa Lucia Fm overlies El Molino Fm. |
Torotoro | S18°03.352' W065°47.833' | Measured section up drainage ~100m S of Julo Grande | El Molino Fm overlies La Puerta Fm. Santa Lucia Fm overlies El Molino Fm. |
Vila Vila | | Measured section up drainage N of Vila Vila. | Problematic section. Believed to be El Molino Fm. Lithology includes calcareous sandstone with brecciated limestone clasts and pebbles. Overlies La Puerta Fm with interbedded basalt flow similar to Incapampa. |
<table>
<thead>
<tr>
<th>Location Name</th>
<th>Coordinates</th>
<th>Location Notes</th>
<th>Stratigraphic Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vilcapuyo</td>
<td>S19°4.012'</td>
<td>Section measured about 5km from the end of the pavement on the Challapata-Potosi road.</td>
<td>El Molino Fm conformably overlies Chaunaca Fm. Santa Lucia Fm overlies El Molino Fm.</td>
</tr>
</tbody>
</table>
VITA

Richard John Fink was born in Atlanta, Georgia, on May 31st, 1966 and raised by Lieutenant Colonel (United States Army retired) Henry John Fink Jr. and Ilse Rehne Fink. Richard attended the Miller School of Albemarle from 1977-81 and graduated from Woodbridge Senior High School in Woodbridge, Virginia, in 1984. After several semesters at George Mason University in Fairfax, Virginia, he enlisted in the United States Navy. Richard served six years in the Navy, working as a sonar technician aboard the fast-attack submarine USS Billfish SSN-676. Following the completion of his enlistment, he moved to Montana where he earned his Bachelor of Science in Earth Sciences degree at Montana State University in 1999. In 1999, he enrolled into the Master of Science program at Louisiana State University where he hopes to graduate in August 2002.