Model of Early Jurassic to Mid-Miocene Geological Evolution of the Back-Arc Sedimentary Basin of Northern Chile and Northwestern Argentina

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Abstract

A model has been constructed from stratigraphic analysis and magmatic emplacement data in which variations of the sedimentary environments of northern Chile and Argentina from the early Jurassic to the mid-Miocene were compiled. From this data a series of maps at 2 million year intervals have been constructed and used to complete an animation depicting the evolution of the regional sedimentary and magmatic systems. This animation was generated using computer facilities at the University of California, Berkeley, running Canvas 6.0 and Ulead GIF Animator software.

During the evolution of the region, numerous transgressive and regressive events occurred causing variations in the lithologies and sediment thickness deposited in various basins. Also apparent from the magmatic emplacement ages is the eastward migration of the magmatic arc from the west coast in the early Jurassic to the present location on the border of Chile and Argentina. Lithologic variations demonstrate the onset of Andean uplift by depicting the rapid accumulation of conglomerates in the basins near the active uplift areas of northeastern Chile in the late Tertiary.

Jurassic transgressions entering from the west caused the magmatic arc to become separated from the coast of South America by a narrow, marine, back-arc basin. Regressions to the west tended to isolate sub-basins, which display distinct sedimentary histories recorded during the regressive intervals. The most extreme example of this occurred in the late-Jurassic (~154 Ma), when large sub-basins were isolated by a marine regression and underwent complete evaporation leading to the basin-wide precipitation of thick deposits of evaporite minerals such as gypsum and halite.

The construction of sedimentary and magmatic depositional environment maps has led to better understanding of the evolution of northern Chile and Argentina, and in particular they allow for the examination of depositional environments present in specific locations for particular time intervals. These observations can assist in the geological interpretation of a region by showing such things as the sediments present in an area during magmatic emplacement.

Current applications of this visualization model include regional provenance studies of chlorine and copper, both of which play essential roles in the varied ore deposits of Chile, Peru, Bolivia, and of Argentina. The model provides critical insight into the positions of key sampling locations necessary to evaluate hypotheses relating the migration of elements via mobile magmatic and aqueous fluids. Modeling of this type affords unique opportunities to investigate the large crustal scale on which transport processes operate during certain periods of geological time.
Figure 1. Location map of the region depicted in the evolution animation.
Introduction

The evolution of the Andean magmatic arc has been the subject of numerous investigations regarding its emplacement and migration, (Ishihara et al, 1984; Petersen, 1999; Sillitoe and KcKee, 1996) and the relationship between subduction and magmatism (Kay et al, 1999; Kay and Mpodozis, 2001) through geologic time. Similarly, studies were conducted investigating the structural development of the Andes, (Dallmeyer et al, 1996; Hartley et al, 2000, 1992; Marquillas and Salfity, 1988; Mon and Salfity, 1995; Reutter et al, 1988) and the sedimentology and stratigraphy of individual areas (Ardill et al., 1994, 1998; Gröschke et al., 1986, 1998; Harrington, 1961; Printz et al., 1994; Von Hillebrandt et al, 1986). This study incorporates all of these styles of data to investigate the geological evolution of the northern Chile, Argentina, and southern Bolivia as a whole from the early Jurassic through the mid-Miocene. The region investigated in this study ranges from 20° to 28° South Latitude and from 65° to 71° West Longitude, (figure 1).

A model has been constructed from stratigraphic, sedimentologic, and magmatic emplacement data in which variations of the sedimentary environments of northern Chile and Argentina from the early Jurassic to the mid-Miocene were compiled. A series of maps have been constructed at 2 million year intervals from this data and used to complete an animation depicting the evolution of the regional sedimentary and magmatic systems. Palinspastic paleogeographic regional maps by Pindell and Tabbutt, 1995 were used to delineate the region to be investigated. These maps depict marine, continental, and magmatic environments from 245 Ma through 1.7 Ma at ~20 million year time intervals. Figure 2 is a representative maps from Pindell and Tabbutt showing these delineation’s. These maps do not distinguish between the various sedimentary lithologies deposited nor indicate the location and timing of magmatic emplacements which are important for this study. The lack of temporal resolution to intervals smaller than 20 million years was also an important factor in undertaking this project.

Sediment isopach maps like figure 3, (Printz et al, 1994) were used to constrain the boundaries between sedimentary environments and areas undergoing active erosion. Future sites of several porphyry copper deposits were plotted on this map to examine the sediment thickness through which the magmatic systems passed and potentially interacted. From figure 3, it can be seen that during the Oxfordian age in the Jurassic, (159 to 154 Ma) a sedimentary basin was actively accumulating sediments. Individual depocenters within the basin show variations in the sediment thickness during this 5 million year interval. These variations are caused by structures which were active during the sediment accumulation. These structures continued to be active throughout the Jurassic and helped to constrain sediment lithologies and their distributions in this area.

Maps depicting large scale events such as figure 4, taken from Marquillas and Salfity, 1988, allowed for sedimentary systems to be correlated to regional and continental scales. In figure 4, Campanian age (~78 Ma) northern Chile and Argentina are shown at the end of a continental rifting stage. The sedimentary lithologies and their distributions were a direct response to large scale events such as the transgression depicted in figure 4.
Figure 2. Middle to late Jurassic, (188 to 145 Ma) palinspastic paleogeographic map from Pindell and Tabbutt, 1994. Dark blue region represents shallow marine environment separated from the pacific ocean by a continuous volcanic arc (green). Marginal basin has good connection with ocean to the North. Colors and future emplacement sites of porphyry copper deposits added by the authors for this study.
Figure 12. Isopach map of northern Chile representing sediments of Oxfordian age, (159 to 154 Ma) deposited in a sallow marine, marginal basin (Prinz et al, 1994). The isopach contours indicate the basin in connected with the ocean in the north and separated in the west by a volcanic arc. Future emplacement sites of the El Salvador, La Escondida, and Chuquicamata porphyry copper deposits were added by the authors.
Many world-class copper and gold deposits are located in the Andes of northern Chile, Argentina, and southern Bolivia (Petersen, 1999; Sillitoe and McKee, 1996; Vila, 1982). Magmatic activity since the early Jurassic is responsible for most of these mineral deposits as well as for the grandeur of the Andean mountains. Some of the major Chilean copper deposits are plotted on figures 1, 2, and 3 to show the proximity of sedimentary units and depositional basins to these later magmatic emplacements. Recently, workers have indicated a potential link between specific sedimentary intervals containing evaporite minerals and economically important copper mineralization in several Chilean porphyry copper deposit (Arcuri and Brimhall, 2000). Occurrences of evaporite lithologies in late-Jurassic, early-Cretaceous, and mid-Tertiary sediments have been documented at various locations throughout the study region (Ardill et al, 1998; Bell, 1989; Flint et al, 1986; Printz et al, 1994; Suarez and Bell, 1987; Suarez et al, 1985). It is these sequences which were investigated for their depositional location, lateral extent, and potential interaction with later magmatic systems.
Data Collection

Data was collected from a variety of sources including fieldwork, published articles, and corporate archives of Codelco, Chile. Vast quantities of data were collected in forms such as stratigraphic columns, geological maps, lithologic facies maps, magmatic emplacement ages, volcanic ash ages, and mineralization ages. Field data was collected over a two-month period in late 1999 while library and corporate archive investigations took place throughout 1999, 2000, and early 2001. A complete bibliography of all compiled data is presented at the end of the animation and is also available for download at the author’s web site at: http://www.ocf.berkeley.edu:80/~tarcuri/. Extrapolation between data points and interpolations through time were done using a facies transition model developed for this project.

The facies transition model was based on several simple assumptions: 1) sediment is transported down-gradient, 2) grain size decreases with increasing distance from the source, 3) erosion is a continuous process on exposed bedrock, and 4) carbonate deposition is suppressed in environments with high clastic input. Using these assumptions a continental lithologic sequence of conglomerate-sandstone-siltstone-shale and a marine sequence of carbonate-shale was developed. It was assumed that all lithologies with a finer grain size than the lithology described for a specific data point would be encountered with increasing distance from that point, down-gradient. For example, a data point of conglomerate transitions into sandstone, siltstone, and finally shale with increasing distance. Multiple points of similar lithology were grouped into fields and lithologic homogeneity was assumed. This model allowed the authors to extrapolate between data points and through time to generate sedimentary environment maps for entire regions.

Geological Evolution

The geological evolution of the study area shows regional and continental scale processes which influenced the type and distribution of the various deposited lithologies. The evolution shows the occurrence of numerous marine transgressions and regressions affecting the continent, with Jurassic events entering from the west and Cretaceous events entering from the east. These processes caused variations in the lithologies and sediment thickness deposited in the various depositional environments. Also apparent from the magmatic emplacement ages is the eastward migration of the magmatic arc from the west coast in the early Jurassic to it’s present location on the border between Chile and Argentina (Sillitoe and KcKee, 1996; Petersen, 1999). Lithologic variations demonstrate active tectonic events, such as continental rifting and the onset of Andean uplift in the Tertiary by depicting the rapid accumulation of conglomerates in basins near tectonically active zones.
The Jurassic Period

The Jurassic sediments of northern Chile have been the subject of numerous studies examining the environment in which they were deposited (Ardill et al., 1994, 1998; Chong and Pardo, 1976; Gröschke et al., 1988; Harrington, 1961; Printz, 1986; and Von Hillebrandt et al., 1986). The tectonic history of the region has also been the focus of works investigating the connection between sediment thickness and forarc development, (Hartley et al., 2000) and sub-basin evolution (Printz et al., 1994). The conclusions of

Figure 5. Evolution maps from the Jurassic period representing 2 million year increments; A) 194-192 Ma, B) 154-154 Ma, C) 146-144 Ma, D) Legend for all maps generated. Variations in lithologies and their distributions can be examined as well as magmatic emplacement ages. No distinction was made between volcanic and plutonic emplacements.
these works are that the Jurassic system consisted of a marine back-arc basin which experienced numerous transgressive-regressive events prior to it’s disappearance in the late Jurassic-early Cretaceous (Printz et al, 1994; Ardill et al, 1998). Jurassic transgressions entered from the west and caused the magmatic arc to become separated from the coast of South America by a narrow, marine, back-arc basin. Subsequent marine regressions isolated sub-basins, which display distinct sedimentary histories recorded during the specific regressive intervals.

Tracking the specific lithologic variations through these basins and over the continent as a whole shows how magmatic and tectonic processes act in concert to influence sedimentary environments. Figure 5 shows several time intervals from the Jurassic in which the focus is the marine back-arc basin. Figure 5A depicts the basin with strong connections to the ocean and a large spatial distribution. As the basin is isolated from the ocean by a marine regression and the development of the coastal magmatic arc, (figure 5B) evaporite minerals such as gypsum and halite precipitate in various sub-basins. Evaporite minerals were deposited at various times throughout Jurassic in several types of depositional environment, (i.e. deep water or sabkha). This process culminated in massive, basin-wide deposition of gypsum in the late Oxfordian, approximately 154 Ma when the basins underwent extreme evaporative concentration (Ardill et al, 1998; Bell, 1989; Gröschke et al, 1986; Printz et al, 1994). In figure 5C the back-arc basin has nearly vanished, with only small sub-basin remaining. These sub-basins continue to deposit sediments in what was originally the deepest part of the original basin.

The Cretaceous Period

Continental scale processes continued to make major changes throughout the study regions during the Cretaceous period. Of these processes, rifting coupled with a transgressive event from the east were the most notable. Marine basins developed in northern Argentina and Bolivia which would later become the focus of major oil and gas exploration. It was this hydrocarbon exploration that motivated the sedimentological studies forming one basis of this work. Compressional events associated with the active subduction zone to the west and extensional tectonics throughout Argentina and Bolivia reactivated Paleozoic faults and allowed for the thick accumulation of sediments in basins which would later be uplifted to for the Bolivian Altiplano (Welsink et al, 1995). The migration of the magmatic arc eastward began in the early Cretaceous and by 90 Ma reached the point where it would be located until the mid-Tertiary (Petersen, 1999).

Continental rifting began in the early Cretaceous which allowed a marine transgression to penetrate far into the continental interior (Marquillas and Salfity, 1988; Pindell and Tabbutt, 1994; Reutter et al, 1988). Figure 6A shows the well developed rift system through Argentina and Bolivia at 90 Ma. Distinct, fault-bounded basins were established at this time, and continued to be active into the Tertiary. This rift continued to expand, allowing a marine transgression at 68 Ma to flood much of the continent (figure 6B). The inland flood of marine waters was bounded on the west by the active volcanic front of the Andes, which constituted a long, linear volcanic highland. West of the Andes volcanic arc, sediment deposits indicate a gradual decrease of elevation down to sea
level, with no evidence of transgression related flooding. A marine regression began soon after 68 Ma, during which the marine waters drained from the continental interiors or were stranded in isolated inland basins. Once again, these inland basins were subject to evaporation leading to the deposition of evaporite sequences as seen in figure 6C.

Figure 6. Evolution maps from the Cretaceous period representing 2 million year increments; A) 92-90 Ma, B) 70-68 Ma, C) 58-56 Ma. The legend displaying the lithologic identifications for these images is presented in figure 5D.
The Tertiary Period

Tertiary regional evolution was dominated by compressional tectonics and continued eastward migration of the magmatic arc. One of the major tectonic events which occurred during the late Tertiary was the uplift of the Andes. The orogeny commenced in the late Eocene and continued well into the Miocene in a series of uplift phases, the Incaica (~38 Ma), the Pehuenche (23-25 Ma), the Quechua (~10 Ma), and most recently the Diaguita (3-5 Ma), (Hartley et al, 2000). Figure 7A shows large fields of conglomerates being shed from the volcanic regions associated with the onset of uplift during the Pehuenche phase, at 24 Ma. The large non-depositing region in western Bolivia is the emerging Bolivian altiplano, which began to form in the early Tertiary (Welsink et al, 1995).

Figure 7. Evolution maps from the Tertiary representing 2 million year increments; A) 26-24 Ma, B) 12-10 Ma. The legend displaying the lithologic identifications for these images is presented in figure 5D.

The magmatic evolution is dominated by the rapid migration of the magmatic arc from it’s Cretaceous location through central Chile to the modern location at the border with Argentina. This migration can be divided into a series of four temporally distinct, magmatic belts which run in continuous parallel positions through most of northern Chile (Sillitoe and McKee, 1996). The magmatic belts have the following progression from west to east: an early Cretaceous belt located mainly in north-central Chile, a Paleocene belt, a late Eocene to early Oligocene belt, and an early to middle Miocene belt only present south of 26° S Latitude. The late Eocene to early Oligocene belt contains many of the world’s largest porphyry copper deposits and has generated much debate as to why this one time interval saw the deposition of such a large quantity of base metal deposits. The active volcanic arc is currently the focus of much exploration related to precious metals such as gold and silver and base metals like copper.
Conclusions

The construction of sedimentary and magmatic depositional environment maps and their compilation into an animation has led to better understanding of the geological evolution of northern Chile and Argentina. In particular, they allow for the examination of depositional and magmatic environments present in specific locations for particular time intervals. These type of maps allow observations to be made which can assist in the geological interpretation of a region. For example, it is possible to investigate the type of sediments present in an area prior to the emplacement of a magmatic system. The could have a profound affect on the way that data collected from the magmatic system was to be interpreted.

Current applications of this visualization model include regional provenance studies of chlorine and copper. These elements are among many which play essential roles in the varied ore deposits of Chile, Peru, Bolivia, and of Argentina. The model provides critical insight into the positions of key sampling locations necessary to evaluate hypotheses relating the migration of elements via mobile magmatic and aqueous fluids as complexing agents of metals. These fluids tend to be either completely or partially responsible for the deposition of various metals forming the deposits of the region. Modeling of this type affords unique opportunities to investigate the large crustal scale on which certain transport processes operate during periods of geological time.

Animation

To view the complete animation, double click on the attached executable file labeled Evolution.exe. The program will take approximately 30 seconds to begin, depending on the computer on which it is being viewed. The animation is presented as a continuous loop, allowing for repeated viewing. All references are presented at the end of the animation. Press the escape key at any time to end the program. Approximate running time is 3 minutes. A complete version of the animation is presented here and is also available for download at the author’s web site: http://www.ocf.berkeley.edu:80/~tarcuri/.

Acknowledgments

The authors would like to express appreciation to the following people; Irene Montero S., Tina Takagi for discussions leading to improvements in the presentation of this material. This project was completed during doctoral research of Terry Arcuri, performed at the Earth Resources Center, University of California, Berkeley and made possible by a grant from Codelco, Chile.

The animation was generated using computer facilities in the Earth Resources Center. Individual map images were generated in Canvas 6.0 by Deneba Systems. GIF Animator 4.0 software from Ulead Systems was used to compile the images and generate the final animation.
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