Mineralium Deposita (2000) 35: 377–384

ARTICLE

G. K. Taylor

Palaeomagnetism applied to magnetic anomaly interpretation: a new twist to the search for mineralisation in northern Chile

Received: 9 April 1999 / Accepted: 5 October 1999

Abstract The Chilean Iron Belt is an important location for Fe and Cu(Fe)-Au deposits and includes the recently developed Candelaria deposit, which is located some 20 km south of the city of Copiapó in northern Chile. This mine is now a major Cu producer in Chile but its discovery in the late 1980s was relatively fortuitous. The exploration programme included a ground magnetic survey from which lessons can be learnt in the search for further such deposits. Palaeomagnetic studies throughout the northern part of the Chilean Iron Belt indicate major crustal rotation of the region, probably, related to oblique convergence and transpression at the Andean Margin. The application of palaeomagnetic techniques to a magnetite-apatite deposit, Mina Fresia, indicates that magnetite-rich ores in this area are capable of maintaining a significant remanence component which will contribute to their magnetic anomaly. As with the volcanics, intrusives and sediments of the region this, remanence is clearly rotated clockwise. Using 2.5D and 3D magnetic modelling, it is demonstrated that the magnetic anomaly associated with the Candelaria deposit is also dominated by a remanence component which is significantly rotated but of reversed polarity. Recognition of clockwise-rotated, remanence-dominated anomalies should provide a new key to the search for deposits in this part of Chile and elsewhere. An example of an unexplored anomaly showing this key feature of a clockwise-rotated remanence component dominating over the induced component is presented. Modelling of this anomaly indicates a pair of sources which are either ten times as big or ten times as magnetic as the Candelaria deposit. It is suggested that the low cost of palaeomagnetic study of an exploration target should be a prerequisite to magnetic anomaly interpretation of targets in tectonic areas where vertical axis crustal rotations may be a significant element of the overall deformation pattern.

Editorial handling: L. Miller

G. K. Taylor
Department of Geological Sciences, University of Plymouth, Drake Circus, Plymouth, PL4 8AA, UK
e-mail: GTaylor@Plymouth.ac.uk
Tel.: +44-1752-233104; Fax: +44-1752-233117

Introduction

The well-known Chilean Iron Belt of northern Chile is a NNE-trending belt of more than 40 iron ore deposits of economic significance located in the central and eastern part of the Coastal Cordillera between 25.5°S and 31.0°S (Ménard 1995; Fig. 1). Mineralisation is commonly linked to magmatic, metasomatic and contact metamorphic processes associated with the emplacement of the Lower Cretaceous plutons of the Coastal Batholith into the surrounding Mesozoic cover sequences. Key structural elements in the location of the deposits, in the northern half of the belt at least, are the intersections of major N-S to NNE-SSW ductile to brittle structures, such as the Atacama Fault Zone, which were involved in the emplacement of the plutons (Grocott et al. 1994), and NW-SE trending sinistral brittle faults (e.g. Bonson et al. 1997).

These controls on mineralisation are all elements of the overall deformation pattern of the over-riding plate at the Andean plate margin. This deformation pattern as a whole is, in general terms, a function of strain partitioning at an obliquely convergent margin into orogen-parallel and orogen-normal components. Most palaeomagnetic studies in northern Chile have been employed to determine the location and magnitude of crustal rotations linked to this strain partitioning. In particular, palaeomagnetic studies throughout this northern part of the Chilean Iron Belt indicate the widespread occurrence of major clockwise crustal rotations (Fig. 2). The initial link between mineralisation and palaeomagnetism was triggered by the recognition that the NW-trending sinistral faults, which in part control mineralisation (e.g. Bonson 1998), are also thought to have played a role in controlling clockwise

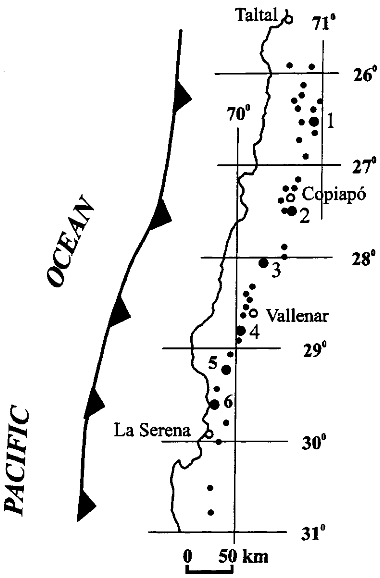

Fig. 1 The Chilean Iron Belt of northern Chile between 25°S and 31°S. The numbered mines are the largest producers/prospects in the belt. *1* Manto Verde, *2* Candelaria, *3* Boquerón Chañar, *4* El Algarrobo, *5* Cristales, *6* El Romeral

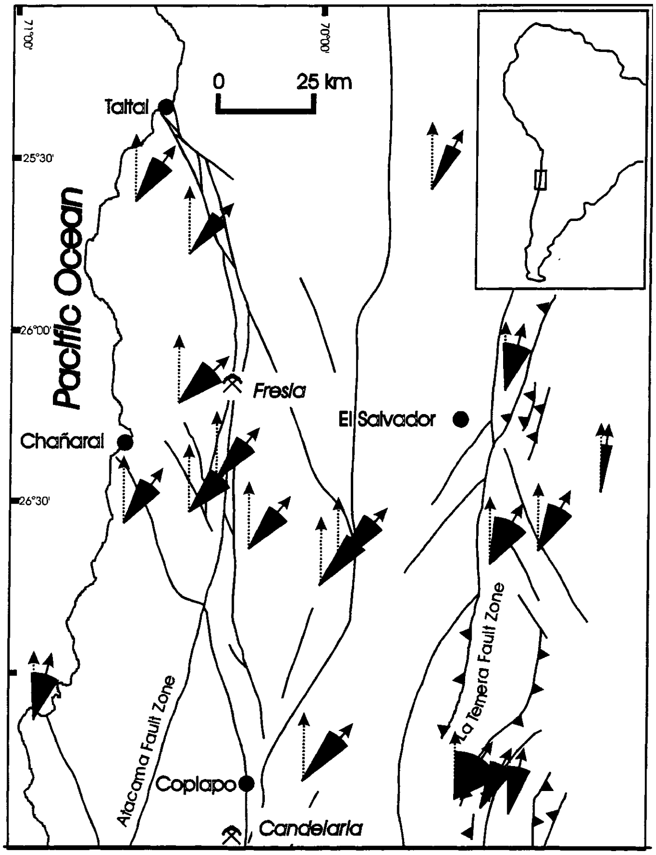

Fig. 2 Sketch map of northern Chile between 25°S and 27°S showing the distribution of palaeomagnetic studies all of which have indicated clockwise rotations in this region. The magnitude of the rotations are given by the difference between the *solid northeastward directed arrows* compared to expected directions indicated by northward pointing *dashed arrows*. The errors associated with the rotations are shown *plotted as arcs* about the *rotation arrow*. Major N-S and NW-trending faults are also shown. (Data are from Forsythe et al. 1987; Riley et al. 1993; Dupont-Nivet et al. 1996; Randall et al. 1996 and in preparation; Taylor et al. 1996, 1998b; and author's unpublished data)

crustal rotations in the same area (Randall et al. 1996). These rotations are thought to result from transpression across these NW-trending faults during oblique subduction at the margin during and after the mid-Cretaceous (Taylor et al. 1998a). More importantly, it is now recognised that palaeomagnetism can play a role in understanding the magnetic anomalies of ore deposits in this region as this work will demonstrate.

The Punta Del Cobre mining belt

The Punta Del Cobre mining belt either forms part of the Chilean Iron Belt or parallels it on its eastern margin depending upon the exact definition of the Chilean Iron Belt adopted. The Punta Del Cobre belt itself is located to the south and east of the city of Copiapó on the eastern margin of the Coastal Batholith where it is in contact with the Lower Cretaceous volcanics of the Bandurrias and Punta Del Cobre formations and Chañaracillo Group limestones (Arévalo 1994, 1995; Marschik et al. 1997 and references therein). Mineralisation is located within the broad metamorphic aureole at the eastern margin of the easternmost plutons which make up the Coastal Batholith. It comprises several Cu(Fe)-Au deposits, the largest of which is the Candelaria deposit (Figs. 1 and 2). This study will show that interpretation of the magnetic anomaly associated with the Candelaria deposit is readily linked to the known palaeomagnetic determined rotations in the area and that knowledge of the remanence vector may well be significant in many cases of magnetic anomaly interpretation associated with mineral deposits in northern Chile.

Palaeomagnetism in northern Chile

Palaeomagnetic studies in the broad region around the Candelaria deposit (Fig. 2) all consistently show large clockwise crustal rotations (Forsythe et al. 1987; Riley et al. 1993; Dupont-Nivet et al. 1996; Randall et al. 1996, in preparation and unpublished data; Taylor et al. 1996, 1998b). On a larger scale this pattern of clockwise rotations is seen to be related to the Arica deflection/Bolivian Orocline whereby palaeomagnetic vectors in the southern (Chilean) limb of the orocline generally indicate clockwise crustal rotation and those from the northern limb (Peru) indicate anticlockwise rotation (e.g. Somoza 1994; Beck 1998; Randall 1998; for recent reviews). These rotations are derived from measurements of the declination of the palaeomagnetic remanence vectors.

A preliminary palaeomagnetic study of the magnetite-apatite deposit at the abandoned mine Mina Fresia (Treloar and Colley 1996; Fig. 2) revealed a stable palaeomagnetic remanence when subjected to standard stepwise alternating field (AF) demagnetisation procedures (Fig. 3). This technique allows the isolation and identification of ancient and modern remanence components in samples. Most samples possessed two components of remanence, a low coercivity component generally directed toward the present-day direction suggesting a recent viscous overprint, and a higher coercivity component. This higher coercivity component has both normal (Fig. 3A) and reverse (Fig. 3B, C) polarities in different samples (normal $n = 5$ samples, declination = 35.1°, inclination = −40.0°, reverse $n = 4$ samples, declination = 210.2°, inclination = 29.9°). The antipodal nature of these directions strongly suggests that this is an ancient component of magnetisation. The overall mean direction ($n = 9$ samples, declination = 32.8°, inclination −35.6°, $k = 21.8°$, $\alpha 95 = 11.3°$) is, within error, the same as that derived from dated Lower Cretaceous dykes from the same

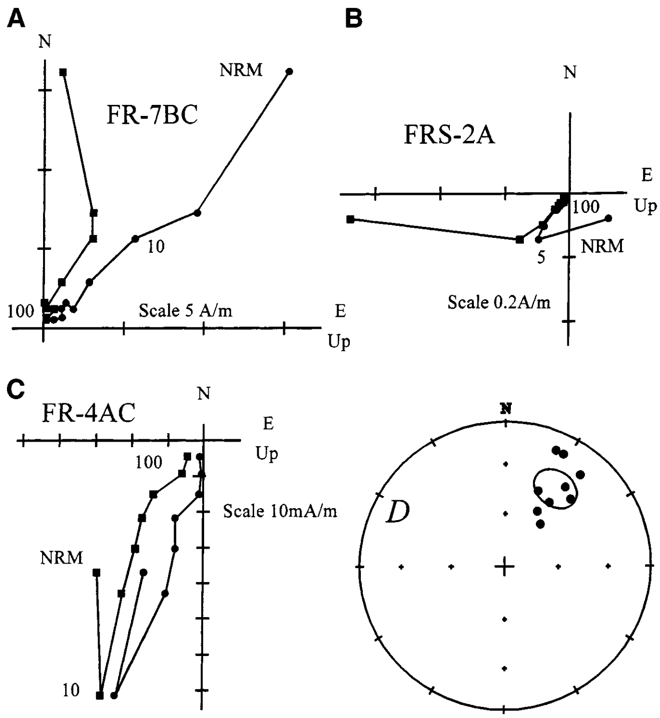

Fig. 3 Palaeomagnetic results of samples from the magnetite-apatite mine Mina Fresia. **A, B, C** show Zijderveld demagnetisation diagrams of the progressive AF demagnetisation of the samples. Horizontal (vertical) projection are shown by *circles* (*squares*), demagnetisation steps are given in milliTesla. **A** shows removal of a present-day component prior to a normal component while **B** and **C** show removal of low components prior to a reversed component. **D** shows a stereonet projection of the determined sample directions and their mean α95% confidence interval

area (Dallmeyer et al. 1996; Randall et al. 1996). This area has both a present-day declination and a predicted Early Cretaceous declination of about 003° (Randall et al. 1996) based on palaeomagnetic study of cratonic units. The discrepancy therefore between the measured remanence declination and the predicted declination indicates that the orebody carries a stable ancient remanent magnetisation and that the orebody has been rotated about a vertical axis by approximately the same amount as the whole area (Fig. 2).

Exploration for economic mineral deposits frequently makes use of ground and aeromagnetic geophysical techniques to detect a characteristic magnetic signature associated with an orebody. Such anomalies arise from both an induced magnetisation component, due to the Earth's magnetic field interacting with the magnetic susceptibility of the deposit, and a remanent magnetisation component due to the intensity and direction of the palaeomagnetic remanence of the body. Only infrequently has the remanent magnetisation of orebodies been documented and the remanent component included in the analysis of such magnetic field anomalies. One important reason for this is that the remanent contribution to the overall magnetic field is commonly small in comparison to the induced field. Furthermore, the measurement of remanence requires specialist field sampling techniques and laboratory studies to determine its nature. In northern Chile, however, Roperch and Chauvin (1997) highlighted the fact that remanence may play an important part in the interpretation of observed anomalies associated with volcanic rocks.

This study seeks to demonstrate that in the case of magnetite-bearing ore deposits located in orogenic belts, where vertical axis rotations are now frequently found to be a common element of the deformation pattern, an understanding of the remanence direction within and around the deposit can play a significant part in the interpretation of magnetic field anomalies. It is clear from the example of Mina Fresia that magnetite-bearing orebodies are capable of acquiring and maintaining an ancient remanent magnetisation and that in the northern part of the Chilean Iron Belt this remanence should be expected to be rotated such that it is orientated NE or SW, depending upon its polarity.

Candelaria

Mineralisation

Candelaria is the largest deposit in the Punta Del Cobre mining belt and has mineable reserves of some 400 Mt at 1.0% Cu, 0.20 g/t Au and 4.5 g/t Ag at a cut-off grade of 0.4% Cu (Martin et al. 1997). Magnetite, although not currently exploited, is ubiquitous throughout the deposit and makes up 10–15% of the mineralised body. It occurs in a variety of forms including sheared and non-sheared veins and breccias, stringers, massive to semi-massive lenses, pods and disseminations as well as inclusions within chalcopyrite, pyrite, pyrrhotite and sphalerite (Ryan et al. 1995; Martin et al. 1997). Consequently, it is interpreted as having developed during both the early metasomatic and the main mineralisation phases of Candelaria's development, although the later phase of magnetite deposition may in fact be a remobilisation of the earlier phase of magnetite development (Ryan et al. 1995; Martin et al. 1997). Pyrrhotite, which is also capable of retaining a magnetic remanence, is much less abundant in the deposit and is typically replaced by pyrite, marcasite and magnetite (Ryan et al. 1995).

Exploration history

The discovery of this major deposit was somewhat fortuitous, as indicated in the history of the exploration of the deposit given by Ryan et al. (1995). Small mines operated sporadically in the area from the 1930s until the early 1980s yielding a small amount of gold-bearing copper-oxide ore. In 1985 a single exploration drillhole encountered a few metres of chalcopyrite but this was abandoned due to a high rate of water inflow. Subsequent geophysical exploration included an induced polarisation survey which located a major anomaly at depth below the previous drillhole and subsequent drilling led to the discovery of the deposit.

Ground and aeromagnetic follow-up surveys were conducted and it is the published ground magnetic survey data (Fig. 4) that forms the basis for the interpretation presented here. Little interpretation was given for this map (Ryan et al. 1995) other than that the anomalies associated with the deposit lay in an area of a high magnetic gradient between higher magnetic susceptibility rocks to the NW (associated with the Coastal Cordillera Batholith) and lower susceptibility rocks to the SE, reflecting the preponderance of limestone in this area. It was also noted that regional aeromagnetic anomalies correlated well with the ground magnetic data

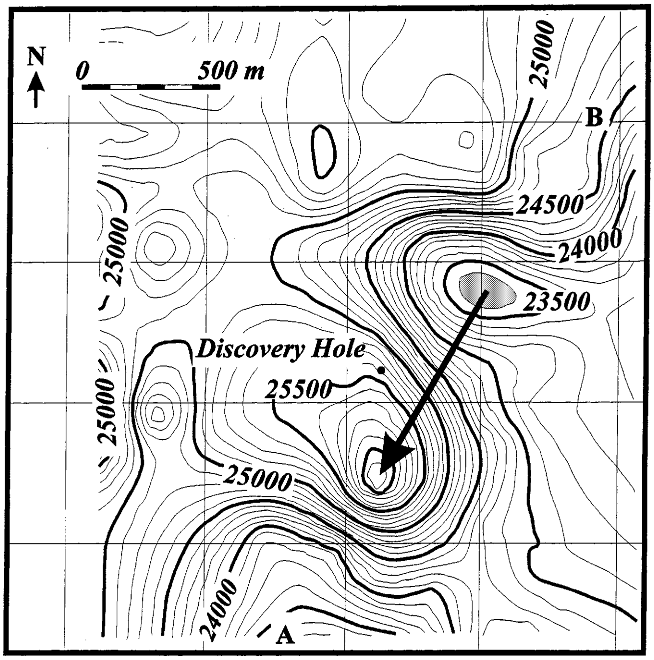

Fig. 4 Total field ground magnetic anomaly map of the Candelaria area (after Ryan et al. 1995). The original discovery hole is located close to the NE-SW trending axis of the anomaly (marked by the *arrow*). Note that the low and high parts of the anomaly are located to the NE and SW respectively, with a subsidiary low to the south marked by the open contours. Grid lines are every 500 m, magnetic anomaly values are in nT, contour intervals are 100 nT and closed magnetic lows *shaded*. *A-B* marks the line of profile modelled in Fig. 6

and led to the discovery of the Alcaparrosa Deposit (Ryan et al. 1995).

Palaeomagnetism

The age of mineralisation in the Punta Del Cobre district is constrained by various geochronological methods to lie between 114 and 117 Ma (Marschik et al. 1997) and certainly no later than 110 Ma. (Arévalo, personal communication 1999). This age range for mineralisation lies within the Cretaceous Long Normal Magnetic Polarity Interval which is an abnormally long period of constant magnetic polarity in the Earth's history. This period extends from the early Aptian to the end of the Santonian (about 120–83.5 Ma on the scale of the Gradstein et al. 1994). No globally consistent reversal of magnetic polarity has been recognised during this period. Hence magnetic remanences formed during this period should be expected to have a normal polarity. Given South America's relatively small amount of movement since the Cretaceous and the available palaeomagnetic database for the craton, the remanence should be directed toward a northerly declination with an upward-directed inclination similar to the present-day field. In such circumstances an interpretation of the magnetic anomaly in terms of its induced component only would be justified. This, however, would assume the absence of tectonic rotations from the region which, as previously discussed, are well documented on palaeomagnetic grounds.

The Candelaria magnetic anomaly

Modelling

The ground magnetic map over the Candelaria deposit (Fig. 4) clearly shows an anomaly comprising a low to the NE and a high to the SW of the discovery hole. Less obviously related to the location of the deposit is the low to the south of the main high. An anomaly arising from an orebody with an induced component only would be expected to give rise to a high to the north and a low to the south of the orebody location (Fig. 5A).

Computation of 3D magnetic anomalies (using a fast Fourier transform method based on Parker 1973) using a ratio of 5:1 for the remanence-induced components has been carried out for comparison with the ground magnetic map. This ratio was found, after an iterative process, to be sufficient to deflect the dipole axis of the anomaly by the required amount. The causative body in these models is a simple, uniformly magnetised, block 1.0 km in length and 0.5 km in width and depth, located in the centre of the area. The magnetic anomaly was computed over an area of 5×5 km centred on the block. The intensity of magnetisation is essentially arbitrary as this only affects the amplitude of the calculated anomalies. Declination and inclination of the remanence are based on the palaeomagnetic directions from the region with conservative estimates of the average rotation giving an assumed normal polarity component of declination 035° and inclination −40° (Fig. 5B) and a reversed remanence direction of declination 215° and inclination 40° (Fig. 5C). These calculated anomalies, with a significant remanence component, differ markedly from that produced by a component of induced magnetisation only. In particular, anomalies generated by significant normal polarity remanence should show a NE-SW axis to the dipolar anomaly with a NE high and SW low (Fig. 5B). Anomalies dominated by a reverse component of remanent magnetisation will cause a more complex anomaly pattern with the high located to the SW and the low to the NE of the body location with a secondary low to the south of the high (Fig. 5C).

Interpretation and discussion

Comparison of the Candelaria magnetic anomaly (Fig. 4) and that for a theoretical body dominated by a reverse and rotated remanent magnetisation (Fig. 5C) suggests a distinct similarity in anomaly pattern. In short, the peak-to-peak axis of the Candelaria anomaly trends 030–210° and the remanent polarity must be reversed, as shown by the significant high over the deposit, and lows to both the northeast and south. These lows are, however, more marked in reality (Fig. 4) than they are in the

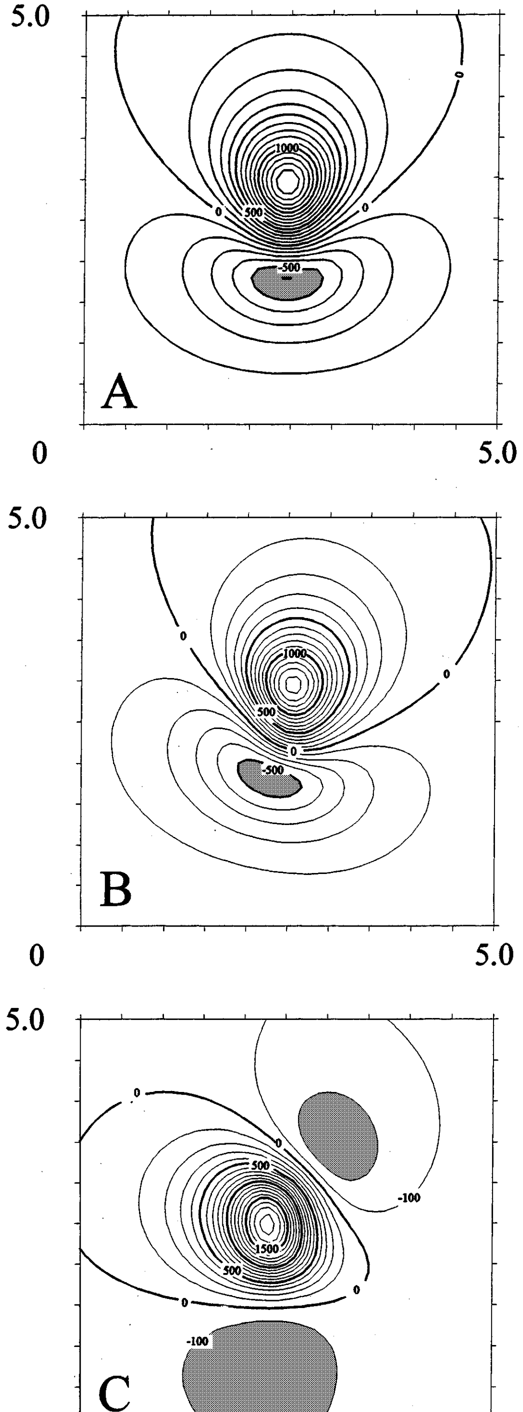

Fig. 5 Theoretical magnetic anomaly maps calculated from 3D magnetic modelling of a simple 1 km long by 0.5 km wide and deep, uniformly magnetised block located in the centre of a 5 × 5 km grid. Contours are shown every 100 and 500 nT and closed magnetic lows *shaded*. **A** Induced component only with declination 000° and inclination −45°, **B** induced plus remanent with a normal polarity remanent vector declination of 035° and inclination of −40° and **C** induced with a reversed polarity remanent vector of declination 215° and inclination of +40°. In both **B** and **C** the remanence intensity is five times the induced component

model (Fig. 5C) which may be a geometrical effect of the simple shape of the body modelled in comparison to the actual 3D shape of the orebody. The axis of the Candelaria anomaly at 030–210° has a smaller clockwise rotation than that observed in palaeomagnetic studies, as should be expected, because of the influence of the induced magnetisation component of the field and would therefore be consistent with a true rotation of some 35° or so as seen throughout the region (Fig. 2).

This analysis was further confirmed using 2.5D magnetic modelling, which is forward modelling of 2D bodies but incorporating end corrections for the strike length of the bodies (Rasmussen and Pedersen 1979), of a magnetic profile taken along the 030° trending axis of the main positive and negative anomalies over the orebody (Figs. 4 and 6). The model was computed, (Cooper 1997) after removal of an average value to crudely approximate the regional field (as the mapped area is not large enough to define the true regional), using a susceptibility contrast of 0.005 cgs and a remanent field of 650 nT. The shape and width of the body (1 km) were approximated from the published cross sections and maps of the mine (Ryan et al. 1995; Martin et al. 1997). Critically it proved impossible to model the body on the basis of its induced component only, instead a strong reversed and rotated remanence component was again found necessary to generate a calculated anomaly which approximates well to the observed anomaly and confirms the validity of this approach (Fig. 6). Clearly, a better match of observed to calculated anomalies could be achieved if more detailed information on the regional field, magnetic parameters and magnetite distribution with depth were available.

Discussion of the interpretation

The Candelaria magnetic anomaly has been shown to be remanence dominated, the remanence having a SW-

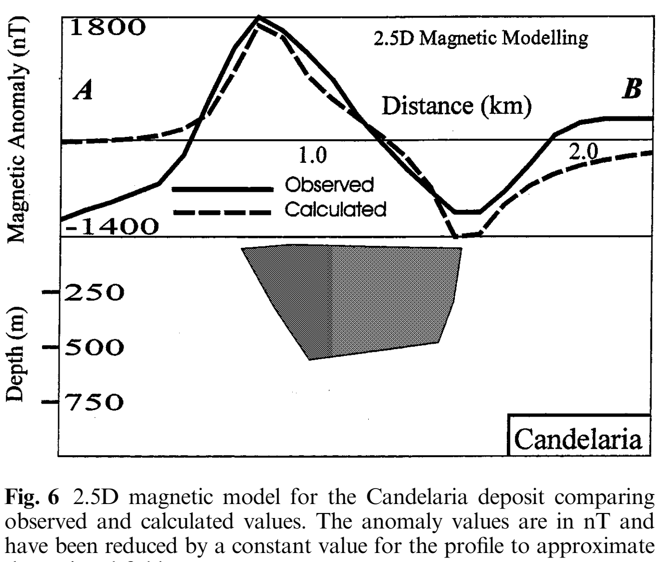

Fig. 6 2.5D magnetic model for the Candelaria deposit comparing observed and calculated values. The anomaly values are in nT and have been reduced by a constant value for the profile to approximate the regional field

directed declination and +ve inclination. This rotation of declination from a north-south axis is consistent with regional findings of major clockwise rotation of the area post acquisition of the magnetic remanence. The reversed polarity nature of the remanence indicates that it is highly unlikely to have been acquired at the time of mineralisation. If one accepts the continuity of a normal polarity throughout the Cretaceous Long Normal Polarity interval, it implies that the Candelaria deposit was remagnetised post 83.5 Ma. This therefore implies two significantly younger events affecting the geological history of the deposit, the first a (low-temperature?) remagnetisation event followed by a tectonic event causing the rotation.

Upward continuation of the modelled Candelaria profile shows that a significant aeromagnetic anomaly would be detected at a ground clearance of 300 to 500 m, typical of many such surveys. The peak-to-peak amplitude is obviously greatly reduced and the continuity and identification of such an anomaly would depend greatly on flight line spacing. To aid interpretation of magnetic maps a commonly employed analytical technique is reduction to the pole (Blakely 1977). This essentially reduces the complex dipolar response of magnetic bodies to a monopolar response akin to a gravity response such that a single anomaly is located directly above a body of interest. It does, however, normally presume that the magnetic anomalies are solely due to an induced field created by the Earth's magnetic field and the bodies' susceptibility. Such an approach when applied to anomalies such as that of Candelaria, which is remanence dominated, will serve to suppress the true nature of the anomaly and produce a marked shift in any predicted location for a target. Identifying anomalies dominated by remanence requires knowledge of the expected remanence and an understanding of what this will do to the shape of the anomalies on raw, unfiltered magnetic maps if and when encountered.

Application of the approach to a potential target

Applying the lessons of the Candelaria deposit, an anomaly with good potential for further exploration was readily identified on aeromagnetic data from northern Chile. This location has all the common geological elements typical of orebodies in the region, i.e. it is located at an early Cretaceous pluton margin which has contact metamorphosed volcanics and lies at the intersection of N-S and NW-SE faults (e.g. Bonson 1998). The aeromagnetic map (Fig. 7) shows a very large, in both amplitude and area, NE-SW orientated anomaly but this time with the high in the NE and low in the SW. This is similar to the 3D theoretical anomaly for a normal polarity, remanence-dominated body previously modelled (Fig. 5B). It differs in detail in that it is more complex and a NE-SW profile (Fig. 8) shows that this is caused by the interference of anomalies from not one but two bodies located closely together. The 2.5D model indicates that both bodies have a magnetisation/depth ratio of about ten times, and widths of two to four times, that of the Candelaria orebody assuming the causative bodies to have similar parameters for the induced and remanent field components derived from the Candelaria model.

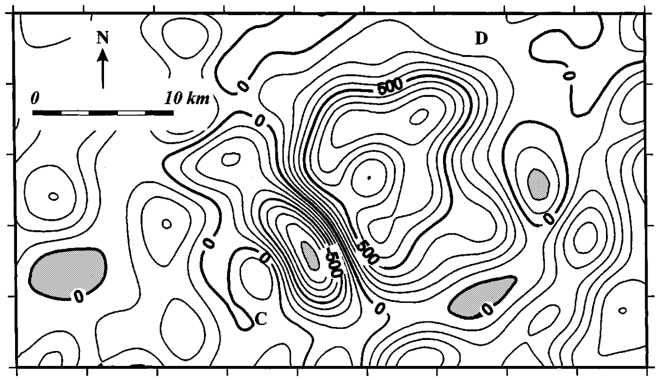

Fig. 7 Total field aeromagnetic map from northern Chile showing a pronounced, but complex, dipolar anomaly with a NE-SW axis indicating that normal polarity dominates over the induced component in the causative bodies. Grid marks are every 5.0 km, the magnetic field is in nT and reduced by a constant background value. Original flight lines were at 1000-m spacing. Contours are shown at 100-nT intervals. *C-D* marks the line of the profile modelled in Fig. 8

Discussion

Having demonstrated that the Candelaria deposit has a reversed and rotated remanent magnetisation, this has a significant impact on the understanding of the tectonic evolution and especially the timing of crustal rotation in northern Chile. The reversed polarity of the remanence implies either that it was acquired during a previously unrecognised short reversal event during the Cretaceous Normal Polarity Superchron or, more likely, that it was remagnetised post-mineralisation. The remagnetisation

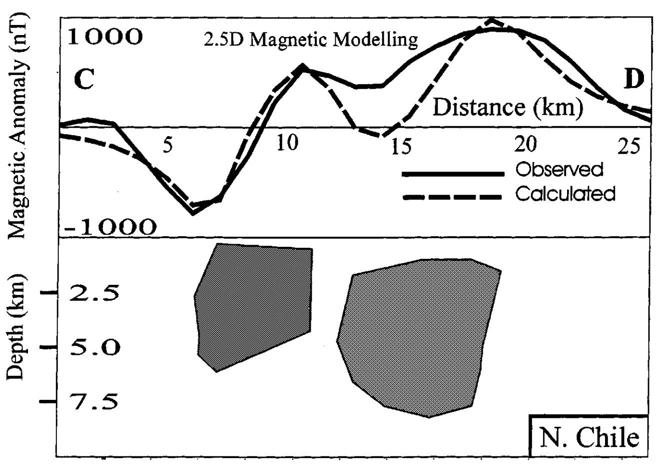

Fig. 8 Magnetic model of the prospective target anomaly discussed in the text. The model indicates two bodies ten times the magnetisation/depth of the Candelaria body and two to four times the width

hypothesis is consistent with the recognition of a remagnetisation event that affects the Cerillos formation rocks which lie to the east of the deposit (Riley et al. 1993; Taylor et al. 1998b, unpublished data). In these rocks the remanence can be shown to post-date folding and pre-date rotation. The age of such a remagnetisation event at Candelaria would then almost certainly have to post-date 83.5 Ma, the end of the Cretaceous Normal Polarity Superchron (Gradstein et al. 1994).

Two alternative suggestions for a remagnetisation event are made, both of which have implications for the understanding of the tectonics of the region and potentially for the location of ore deposits. The first alternative is a Palaeocene reheating event which may have affected the Punta Del Cobre belt based on the presence of minor Palaeocene intrusives to the east of the belt (Arévalo 1994, 1995) and as tentatively suggested on the basis of low initial step ages in incremental heating Ar-Ar experiments on samples closely associated with the mineralisation (Marschik et al. 1997; Arévalo, personal communication 1999). The second alternative hypothesis for remagnetisation could be orogenic fluid flow, the expulsion of fluids from sediments during folding and uplift, perhaps linked to the main Incaic phase of Andean Orogeny. Such early to syn-tectonic remagnetisations are becoming commonly recognised in many compressive orogenic belts throughout the world.

In either case an age of Palaeocene or younger for the remagnetisation event would imply that crustal rotation is considerably younger than the proposed ca. 100 Ma mid-Cretaceous (Randall et al. 1996) or 80 Ma late Cretaceous ages for rotations in the Coastal Cordillera (Taylor et al. 1998a). Equally, both hypotheses imply a low temperature event resetting the magnetic signature of the orebody, during the Tertiary, which may have led to further mineralisation. Evidence for a Tertiary age mineralisation phase is seen in the south of the Chilean Iron Belt. Here, in a very similar setting to that of the Punta Del Cobre belt, silver deposits of Tertiary age are known to post-date the main early Cretaceous Fe-Cu mineralisation (Oyarzun et al. 1998). Further knowledge of such an event could be important in geological exploration models for the location of new targets in this region.

Conclusions

Both 2.5D and 3D magnetic modelling results indicate that the Candelaria magnetic anomaly is only compatible with a strong remanent field with an assumed declination of 215° and inclination of 40°. Assuming average magnetic parameters for the magnetite susceptibility, a remanence contribution of five times the induced component is found to provide a viable model for the Candelaria magnetic anomaly after constraining the depth of the body using published cross sections for the deposit. The orientation of the remanence vector is consistent with the orebody having acquired its remanence prior to having been rotated clockwise as observed in all the regional palaeomagnetic data.

Other such remanence-dominated anomalies exist in northern Chile and the importance of remanent magnetisation should not be underestimated in the future search for other ore deposits in this region and elsewhere. Indeed, this insight is applicable throughout much of the Andes, given the widespread recognition of palaeomagneticaly detectable vertical-axis rotations. As the locations of many ore resources globally are in zones of oblique convergence or divergence, identification of crustal rotations from palaeomagnetic observations of remanence should be seen as prerequisite to many more magnetic anomaly interpretations than is currently the case. Furthermore, given the high cost of geophysical exploration, remanence determinations by palaeomagnetic techniques are an insignificantly small factor in an exploration program but could yield significant insight into the interpretation of magnetic anomalies for the location of ore deposits both in Chile and elsewhere.

Acknowledgements Palaeomagnetic studies in northern Chile are supported by N.E.R.C. grant GR3/11199. I thank Chris Bonson for permission to use the data from Mina Fresia and for many interesting discussions in the field regarding the ore deposits of the area. My understanding of the setting of the Candelaria deposit was greatly helped by a field trip to the Candelaria area led by Carlos Arévalo and the ensuing discussions with John Grocott, Constantino Mpodozis, Walter Martin, Richard Levaille, Robert Marschik and others at the time. I also thank Constantino Mpodozis for granting access to digital aeromagnetic data from northern Chile acquired by the Servicio Nacional de Geología y Minería of Chile and Russ Evans and Zygmunt Dabek of the British Geological Survey for the 3D modelling. Chris Bonson and an anonymous referee are thanked for their constructive suggestions for the improvement of the manuscript.

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