An asteroid impact in the Pacific may have triggered a cascade of tectonic events leading to formation of the mid Cretaceous Chilean Iron Belt

El impacto de un meteorito en el Pacífico podría haber desatado una cascada de eventos tectónicos que habría llevado a la formación de la Faja Cretácica de Yacimientos de Hierro de Chile

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Abstract

A cascade of tectonic and magmatic events that took place in the Pacific and northern Chile during mid Cretaceous led to formation of one of the World's largest Kiruna-type iron belts with reserves of ~ 2000 Mt (60% Fe), a unique case in the geological history of Chile. Geological evidence indicates that a major change occurred in mid Cretaceous time, when superplume emplacement and plate reorganization processes took place in the Pacific. Although this scenario is well documented, no proposals have been put forward on the actual event that may have triggered the subsequent cascade effect. Unusual events require unusual perspectives for their analysis. We know that a large meteoritic impact in the Pacific may have initiated massive volcanism leading to formation of the Ontong Java Plateau. In this respect, we go further proposing that such an impact may be the geologic equivalent to the falling domino principle: once the first piece is knocked over, the rest fall quickly. Thus, once the meteorite impacted the mid Pacific, subsequent and sequential plume emplacement, massive volcanism, plate reorganization, increased plate stress along the Pacific margin, fault zone formation and emplacement of the Chilean Iron Belt (CIB) would have taken place within a relatively short time span in mid Cretaceous time. Thus, we propose that formation of the CIB could be fully regarded as an integral part of the far reaching consequences derived form a large meteoritic impact in the Pacific.

Introduction

"Coincidence is the word we use when we can't see the levers and pulleys" (Emma Bull; in Zambetti 2006). In 2003 the authors of this note suggested a potential plate tectonics scenario leading to formation of the mid Cretaceous Chilean Iron Belt (CIB) (Oyarzun et al. 2003). In that paper we indicated that a major change occurred in late Neocomian time, when superplume emplacement (Mid Pacific Superplume) (Larson 1991; Vaughan 1995) and plate reorganization processes took place in the Pacific. The superplume event resulted in major ridge-push force, overwhelming slab-pull at subducting margins, with the final result of increased coupling between the subducting and overriding plate (Vaughan 1995) (Fig. 1A). In turn, these events would have completely changed the tectonic setting of northern Chile, ending the Early Cretaceous extensional period (aborted rifting in the back-arc basin), and increasing stress at a crustal scale (Fig. 1B). We went further, suggesting that overpressurized dioritic magmas were pushed up mainly along the best possible structural path in northern Chile, that is, the large Atacama Fault Zone (AFZ) (Fig. 1B), eventually forming a +500 km long belt of Kiruna-type iron deposits with reserves
of ~ 2000 Mt (60% Fe), a unique case in Chile’s geological history (Ménard 1992; Oyarzun et al. 2003) (Fig. 2). Although we keep supporting this tectonic scenario, we go a step further suggesting that initiation of massive volcanism and plate reorganization in the Pacific may have initiated after a large meteorite impacted this realm. In this respect, impact cratering has been an ongoing and recurring geological process throughout the history of the planets (including Earth), that operates at many scales and has substantial geological, environmental, biological consequences, and can even force large geodynamic events (Head 2001; Glikson 2008). Besides, the linking of ore deposit formation to meteorite impacts is not new, and a remarkable example of this connection is provided by the giant crater, igneous complex, and nickel ore deposits of Sudbury in Ontario, Canada (e.g. Therriault et al. 2002; Mungall et al. 2004; among others). However, different from Sudbury, other, different links can be traced between impacts and ore deposit formation. As we argue in this paper, impact processes may not be directly involved in the actual formation of an ore deposit, but can trigger nonetheless an unstoppable chain of events in cascade that will ultimately lead to the development a full scale metallogenic scenario.

Basis for a speculative model

Part of our proposal is based upon the observations and calculations made by Bottke et al. (2007), who studied the catastrophic disruption of the parent body of the asteroid Baptistina. The asteroid broke up at about 160 Ma ago in the innermain asteroid belt, and would have led to generation of large fragments that have been slowly delivered by dynamical processes to orbits where they could strike the terrestrial planets. This is the so-called Baptistina Asteroid Family (BAF). Bottke et al. (2007) went further, indicating that this asteroid shower was the most likely source (90% probability) of the Chicxulub impactor. In this respect, our story has nothing to do with the famous K/T boundary but with events that took place some 50 Ma earlier, closer to another stratigraphic transition (Aptian-Albian: 112 Ma), and within a different plate tectonics scenario (Pacific) (Fig. 1A, 3).
From our perspective, several elements are crucial for the revisited CIB scenario. On one side we have the Baptistina asteroids, hitting terrestrial planets since the parent asteroid broke up, on the other, seemingly unconnected facts that can nevertheless be part of the same story. Major events to be considered here are: 1) Superplume emplacement and development of the Ontong- Java Plateau (OJP) (the largest known flood basalt province on Earth) in the Pacific, beginning at ~ 120 Ma (Larson 1991; Vaughan 1995; Ingle and Coffin, 2004) (Fig. 1A); and 2) formation of the large CIB at 128-100 Ma, with a peak at 115-110 Ma (Oyarzun et al. 2003) (Fig. 1B, 2).

Superplume emplacement and subsequent development of the OJP had far reaching implications at the Pacific scale, including high production of oceanic crust at mid ocean ridges (Larson 1991; Vaughan 1995), increased ridge-push force and coupling between the subducting and overriding plates, and uplift, deformation, and metamorphism along the Pacific margin (Vaughan 1995). As far as the northern Chilean realm is concerned, the basin was uplifted, and no more marine episodes were further recorded after this episode; besides, volcanic activity along the arc decreased dramatically, and the large Atacama Fault Zone began its development. It is precisely along this tectonic domain that the CIB formed (Fig. 1B) (Oyarzun et al. 2003). This period is also marked the onset of cooling and uplifting of the arc which eventually shifted to an eastward position by mid Cretaceous time (Scheuber et al. 1995). At a larger scale, it is also during this period that massive accretion of mafic-ultramafic complexes started in Colombia and Ecuador (e.g. Nivia 1996; Hughes and Pilatasig 2002).

The OJP and CIB revisited scenario

A central part of our argument in the early paper (Oyarzun et al. 2003) was the link between the emplacement of a large plume in the mid Pacific and formation of the CIB during a major plate reorganization event. However, the main issue here is whether such Pacific superplume (Larson 1991) and therefore the OJP had a deep mantle (e.g. in the D" layer, sensu Schott and Yuen, 2004) or a shallow origin triggered by a meteorite impact. In this respect, there are arguments based on numerical simulations that rule out a firm relationship between asteroid impacts and volcanism (Ivanov and Melosh 2003). However, as also noted by Glikson (2003), there are crustal and petrologic factors that greatly increase the probability of impact-triggered volcanism in geothermally active regions of oceanic basins. The latter is also
supported by the more recent numerical analysis of Elkins-Tanton and Hager (2005), who indicate that large meteoritic impacts on thin lithosphere (as we can expect in ocean basins) can indeed trigger the onset of large basaltic provinces. According to Ingle and Coffin (2004) there are sound arguments ruling against a deep mantle model for the OJP plume: 1) the absence of a hotspot track; 2) minor early crustal uplift associated with a super plume emplacement; and 3) minor late total subsidence compared with normal oceanic crust or other oceanic plateaus and submarine ridges. Instead, a meteorite impact origin for both the plume and the OJP (Fig. 1A) is favoured by: 1) high degrees of melting at shallow upper mantle depths; 2) low water contents of basalts; 3) enrichment of platinum group elements in basalts; and last but not least 4) because a ~300 km deep, seismically slow mantle root is much more consistent with the consequences derived from the impact of an asteroid colliding with the Pacific ocean floor. Ingle and Coffin (2004) and Jones (2005) suggest that these events could have been triggered by the impact of an asteroid ~20-30 km (diameter) on relatively young (~10-20 Ma) Pacific lithosphere. This would have resulted in large decompression melting in the upper mantle and initiation of massive volcanism at the OJP site. Although this may well explain massive volcanism at the OJP, the question regarding the mantle plume remains: how could an asteroid impact trigger such a plume? In this regard Jones et al. (2002) indicate that the withdrawal of a large volume of melt from the mantle (materials that ascend to feed the superficial volcanism) would lead to mass up-flow of the upper mantle into the vacated space, which in turn would lead to further melting. In this case, we would be dealing with impact-derived or simply, impact plumes (Jones et al. 2002).

Different to impacts on continental crust where morphological (e.g. crater rims) and mineralogical evidence (e.g. shattered quartz grains) can be obtained in the field, a large impact with subsequent massive volcanism on oceanic lithosphere would leave few clues if any. First, no quartz is to be found in oceanic lithosphere, besides a huge volcanic plateau such as Ontong Java would erase any morphological signatures left by an impact: the oceanic lavas would fully blanket the area. As indicated by Elkins-Tanton and Hager (2005), most craters of the age and size seen on the moon are obliterated on Earth through processes of plate tectonics and erosion, whereas others would be obscured beneath the existing large basaltic igneous provinces. In this respect, we are fully aware of the fact that we cannot prove beyond any reasonable doubt that a large body impacted the Pacific by mid Cretaceous time. However, we also believe that it is likely that this may have happened because of the following reasons. On one hand the model of Bottke et al. (2007) indicates that Earth was subjected to intense bombardment of meteoritic bodies at ~ 30 to 60 Ma after BAF formation (at 160 Ma) (Fig. 3).

![Fig. 3: The Baptistina Asteroid Family (BAF) impact rate on Earth through time after its formation at 160 Ma (modified after Bottke et al. 2007). CIB: Chilean Iron Belt. D: Crater diameter. OJP: Ontong Java Plateau.](Fig. 3: Tasas de impacto en la Tierra de la Familia de Asteroides Baptistina.)
On the other, this time span perfectly matches the age range of the CIB: 128-100 Ma and initiation of volcanism at the OJP (Fig. 3), which in turn can be regarded as derived from an impact plume (Jones et al. 2002). Besides, it might not be a coincidence that it is precisely during this time span when a BAF derived body impacted the surface of the Moon, forming the huge crater Tycho (109 Ma; Bottke et al. 2007) (Fig. 4). In this respect, multiple impact episodes (derived from fragmented asteroids or comets) are not regarded as rare events (e.g. Spray et al. 1998; Keller et al. 2003), a phenomenon that is now well exemplified by the sequential impacts of the disrupted comet Shoemaker-Levy 9 with Jupiter in 1994 (Spray et al. 1998). Jupiter, a huge planetary body, is ‘a difficult to miss target’, the Moon is not. Furthermore, if the idea of a mid Cretaceous large impact in the Pacific is correct, then it could also have far reaching implications, for example, as an additional explanation for the origin of the late Aptian-early Albian ‘cold snap’, a time span characterized by global cooling as indicated by sedimentological observations and oxygen isotope data (Mutterlose et al. 2009).

**Final remarks**

William Bragg said that the important thing in science was not so much to obtain new facts as to discover new ways of thinking about them (Braga and Grepioni 2000). In this regard we would like to think that this note opens new ways for the understanding of the mid Cretaceous Pacific scenario and therefore, for the CIB. We already related the origin of the belt to superplume emplacement, increasing stress at a crustal scale, and overpressurized dioritic magmas pushed up along the best possible structural path in northern Chile: the large Atacama Fault Zone (Oyarzun et al. 2003). Unusual, time-related combined events such as formation of the OJP, plate reorganization in the Pacific, massive emplacement of mafic-ultramafic complexes along the Colombian and Ecuadorian Andes, and formation of the CIB may in turn require unusual perspectives for their analysis. If the OJP was indeed initiated by a large impact (Fig. 4), as sound scientific arguments indicate, then it follows that the cascade of tectonic, magmatic and metallogenic events are related to that impact.

Fig. 4: Above, formation of the Baptistina Asteroid Family (BAF); below left, impact of a BAF asteroid on the Moon forming the giant crater Tycho (109 Ma); below right, according to this work: a coeval potential impact on the Pacific. Figure: from Southwest Research Institute.

As expressed above, these events would be the geologic equivalent to the ‘falling domino principle’: once the first piece is knocked over the rest fall quickly. Perhaps ‘quickly’ is the keyword here, because plume emplacement, volcanism, plate reorganization, increased plate stress along the Pacific margin, fault zone formation and emplacement of the Chilean Iron Belt all took place within a relatively short time span. If we are correct, then a large meteorite impact would have been that initial domino piece that made the others fell. We are not implying that everything occurred overnight, but quick enough in geological terms to be regarded as a rather
unique collection of chained events, that nonetheless would have started with a single, almost instantaneous massive release of energy in the Pacific. Thus, formation of the CIB could be fully regarded as an integral part of the far reaching consequences derived from a large meteoritic impact (Fig. 4).

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