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Origin of Large Igneous Provinces: The importance of a definition

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ABSTRACT

In the original definition of a Large Igneous Province (LIP) much emphasis was put on the "extraordinary" character of these provinces. Such emphasis might have contributed to bias the form in which these provinces are commonly visualized, and consequently has contributed to the selective acceptance of genetic models. To avoid such bias, in this chapter the various available definitions are examined, taking into consideration the rules of logic that help us to avoid fallacies. From these definitions, the most critical parameters are identified, and an alternative model of formation of LIPs is advanced. The model developed here envisages LIPs as an extreme of a continuum in volcano-magmatic processes that are produced by essentially the same underlying processes. The differences between LIPs and non-LIPs are conceived as the result of different conditions present in a particular region, but that nonetheless have nothing extraordinary. Although the model developed here is one of several possible alternatives, by having identified the most common fallacies surrounding a LIP, even from its very definition, it might be possible to assess those alternative models in a more equilibrated form in future works.

INTRODUCTION

Large Igneous Provinces, or LIPs, were defined more than a decade ago as "voluminous emplacements of predominantly mafic *extrusive and intrusive* rock whose origins lie in processes *other than 'normal'* seafloor spreading" (Coffin and Eldholm, 1992, p. 17). This definition has marked much of the research done on the subject ever since, as LIPs have been almost unanimously considered to represent periods of *anomalously high magma production rates*. Thus, the essential interpretation of LIPs as events of an extraordinary character likely "to record periods when the outward transfer of material and energy from the Earth's interior operated in a *significantly different mode* than at present" (Mahoney and Coffin, 1997b, p. ix) has been a common feature of the vast majority of papers published on this subject over the past 15 yr. Actually, the emphasis put on the presumed anomalous magma production rate required to explain both the extrusive and intrusive components of LIPs is shared by essentially all genetic models, whether they are associated with the arrival of a mantle plume to the surface of the Earth (Eldhom and Coffin, 2000; Hooper, 2000; Richards et al., 1989; White and McKenzie, 1995), or to different processes of global scale (e.g., Abbott and Isley, 2002; Coltice et al., 2007; Hales et al., 2005; Jones et al., 2002; King and Anderson, 1995; Mutter et al., 1988; Sheth, 1999a; van Wijk et al., 2001).

To better appreciate the influence of the above definition of LIPs in the research made on the subject, I marked with italics key words that somehow predispose us to look for "extraordinary" explanations for these natural phenomena in exactly the same form that saying "do not think of a white elephant" almost invariably brings to the mind of the person hearing that message the image of such an animal, even if briefly. To some extent the problem surrounding any definition of a LIP was identified by Menard (1969) when he said that "the central problem is satisfactorily defining normal." Actually, this is a central problem that we need to face every time that we attempt to organize natural

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phenomena (not only LIPs) in any sort of classification scheme, therefore making it necessary to examine very briefly what the purpose of any classification is.

In the words of Best (1982, p. 20), "Classification is a human endeavor that attempts to recognize . . . common or contrasting features of related things . . . [although it should not be] an end in itself, but a means of seeing more clearly, simply and unambiguously the interrelations of the different properties of different rocks." According to him (p. 20), the objective of classification is therefore subdividing the continuous spectrum of a given property "in some meaningful way" that could help us to make a genetic interpretation of such diversity. As Best further recognized, usually there are thousands of possible forms to conceive a classification scheme, yet not all of the possible classifications are equally helpful for the identification of factors that are significant in the understanding of the genesis of the object of study. A corollary of such diversity is that some classification schemes might predispose us to make selective judgments based in the apparent order artificially introduced by the classification scheme itself. Consequently, the classification scheme exerts an often overlooked influence in the creation of genetic models, and it is important to keep in mind such influence if an unbiased interpretation of observations is really to be made.

The predisposition for a selective interpretation of observations introduced by a particular definition scheme not only represents a typical example of circular reasoning, but actually it could mark the beginning of what Dickinson (2003) has described as the *modern mythic style of thinking in geosciences*. Using the vocabulary of logic (Copi and Cohen, 1994), the characteristic aspect of mythical thinking is the selective assignment of truth values to some of the premises used in the interpretation of observations, sometimes in a very subtle form, but nevertheless favoring an a priori accepted conclusion. Consequently, to avoid mythical thinking it is extremely important to have definitions leading to classification schemes that are as unbiased as possible, yet at the same time allow us to recognize meaningful aspects that can be interpreted genetically. In this chapter I examine several aspects of the current, and two other more recent, definitions of LIPs, aiming to identify the elements with the largest potential to yield significant clues that could help us to better understand the genesis of LIPs and their relation to other manifestations of volcano-magmatic activity in our planet. In the second part of the chapter, I develop an alternative model for the genesis of LIPs that takes into consideration some of the physical constraints identified as more significant in the first part. As it turns out, the model proposed here is a special case of the general model of volcanism proposed by Cañón-Tapia and Walker (2004), and consequently it also contributes to a better understanding of the relation that exists between LIPs and other manifestations of volcano-magmatic activity in our planet. At the onset, it should be clear that the proposed model does not pretend to be a final and definitive answer to every possible question concerning the formation of LIPs, and it has much room for improvement concerning its predictive capabilities in particular from a compositional point of view. Nevertheless, I consider that this model provides an example of the form in which mythical thinking can be avoided in the study of this type of province. Other consequences of having good definitions in science, and in particular in the context of volcanic activity, are examined in the chapter by Szakács (this volume).

TWO RECENT DEFINITIONS OF A LIP

Very recently Sheth (2007) suggested the need to reexamine the currently accepted definition of a LIP quoted at the beginning of this chapter. The motivation for Sheth's suggestion seemed to be unrelated to the above considerations concerning the key role played by a definition and its associated classification scheme, but nevertheless reflecting some concern for such issues. In any case, Sheth's (2007) proposed definition of a LIP comprises the area covered by the igneous rocks present in a given province, so that any place where more than a threshold area is covered by igneous rock (he proposed this threshold to be >50,000 km^2) should be called automatically a LIP. Evidently, by adopting this definition, the bulk of the present-day ocean floor becomes the largest LIP that has ever existed in the geologic history of our planet, which is diametrically opposed to the explicit exclusion of ocean spreading from the group of LIPs made by the definition of Coffin and Eldhom (1992). Other departure from the original definition of a LIP found in the work by Sheth (2007) is that he devised a hierarchical system in which LIPs are subdivided in different categories depending on (1) whether the rocks of the province are extrusive or intrusive and (2) on the predominant composition of the rocks found in that province. Thus, at the first hierarchical level LVPs would stand for "Large Volcanic Provinces" and LPPs for "Large Plutonic Provinces" independently of rock composition. At the second hierarchical level, terms such as LRPs standing for "Large Rhyolitic Provinces," LGPs for "Large Granitic Provinces," or LBPs for "Large Basaltic Provinces" would be required. A most appealing aspect of such a classification scheme is that it contains more subdivisions than a scheme based in a "LIP" versus a "non-LIP" scheme inherent in the definition of Coffin and Eldhom (1992). The increased number of groups with contrasting differences in Sheth's definition might in principle facilitate the task of identifying the significant aspects of the formation of each type of province more easily than it could be possible if only two large groups are defined. In turn, such distinction might prove to be an advantage if the mechanisms controlling the genesis of each type of province are really different among the various groups of the classification scheme. Thus, by allowing ourselves to work with different subtypes of provinces we are more likely to identify processes that might not apply to every subtype, therefore increasing our understanding of these natural phenomena more rapidly than we would have done had we insisted in keeping together all of the provinces in one single class.

The revised definition of a LIP proposed by Sheth (2007), however, is not the only definition that has been advanced recently. Very soon after Sheth's work was published, Bryan and

Ernst (2008) proposed an alternative revised definition of a LIP. The classification scheme proposed by these authors also recognizes that the original definition of the term *LIP* made by Coffin and Eldhom (1992) might have become inadequate to convey the most recent discoveries. Consequently, Bryan and Ernst considered that a new set of criteria should be adopted before assigning to a particular province the status of a LIP. In particular, Bryan and Ernst (2008) suggested that age, crustal and tectonic settings, the predominant intrusive or extrusive character of the rocks, their composition, area, volume, and rapidity of emplacement should all be considered an integral part of the definition of a LIP. Thus, by combining all of these factors Bryan and Ernst (2008) proposed the following definition: "LIPs are magmatic provinces with areal extents >0.1 Mkm^2, igneous volumes >0.1 Mkm^3, and maximum life spans of ~50 Myrs that have *intraplate tectonic settings or geochemical affinities,* and are characterized by igneous pulse(s) of short duration (~1–5 Myrs), during which a large proportion (>75%) of the total igneous volume has been emplaced." Although this definition is much more complex than the original definition issued by Coffin and Eldhom (1994), the hierarchical scheme of classification associated with the new definition only has one hierarchical type allowing distinction of oceanic and continental LIPs, because the rest of the criteria incorporated in the definition are used simultaneously to give place to the various categories listed in the second hierarchical level. In practice, this means that although criteria such as age or intrusive versus extrusive character might be used to attach some labels, all of them have the same hierarchical weight and consequently do not favor the identification of independent genetic processes.

At first sight, the Bryan and Ernst definition seems to be an improvement relative to the definition made by Coffin and Eldhom (1992). On closer inspection, however, it is seen that these two definitions have the same weakness, indicated by the italics that I inserted in them both. Indeed, including a tectonic setting and presumably an associated geochemical affinity in the form done by Bryan and Ernst (2008) actually favors the selective interpretation of observations from within the classification scheme. Note that such a bias is not found in the scheme proposed by Sheth (2007), in particular regarding geochemical composition, because the latter scheme is descriptive and allows for the inception of different LIP subtypes should the need arise (i.e., the lack of enough data to form a hierarchical subtype at present does not exclude its probable eventual creation if future observations reveal that a large enough group with such a distinctive characteristic does indeed exist in nature). In contrast, in the definition proposed by Bryan and Ernst (2008), geochemistry is used as an exclusion criterion leading to a "LIP" versus a "non-LIP" classification scheme that might not account for a diversity of independent LIP subtypes. Consequently, this aspect of the definition proposed by Bryan and Ernst (2008) seems to be opening the doors for the occurrence of mythical thinking in the subject, in exactly the same form that the previous definition by Coffin and Eldhom (1992) did when referring to LIPs as "due to processes other than normal."

Having said this, it is necessary to recognize that the strong emphasis made on the size of the area covered by the rocks in the scheme proposed by Sheth (2007) might hamper the identification of common or contrasting features that might turn to have a genetic significance. The main question is not whether the threshold value should be 50,000 km^2 or 100,000 km^2, inasmuch as the fact that the definition advanced by Sheth (2007) is independent of time. As pointed out by Bryan and Ernst (2008), given sufficient time basically all processes responsible for the generation of magma will produce igneous rocks of LIP-scale dimensions. Consequently, the introduction of time as a parameter in the classification scheme seems to be an important feature that might contain clues concerning the genesis of this type of provinces. Unfortunately, such a parameter is excluded from Sheth's definition.

In summary, while it is apparent that the original definition of a LIP proposed by Coffin and Eldhom (1992) has been superseded by the research made in the past 15 yr, it would seem that we still lack a satisfactory form for classifying this type of natural phenomena. From my point of view, such a lack of clarity in a classification scheme has contributed at least in part to favor mythical thinking in the study of LIPs for all of these years. Whereas the more recent definitions of a LIP take steps in order to avoid such biases, there are still voids in the current definitions that need to be addressed before actually being able to have a truly unbiased interpretation of observations. Some of these issues are examined in the following sections.

OBSERVATIONS AND INFERENCES ON LIPs AND NON-LIPs

An underlying issue in the debate of the origin of LIPs is their probable relation with an extraordinary behavior of Earth's interior during their formation. Establishing what is "normal" and what is not, however, is a rather difficult task for several reasons. For instance, almost every geoscientist would agree when saying that at present there is no evidence suggesting that a LIP is being formed anywhere in the world. Based on such an observation, we might conclude that the present situation represents the "normal" case. Nevertheless, it is equally valid to assume that the scenario leading to the formation of LIPs is the normal situation, and that we are nowadays passing trough a time of "abnormal" activity. In this sense it can be argued that LIPs have been fairly common throughout Earth's history when regarded as a group and not on a one-to-one basis (see references in Ernst et al., 2005; Macdougall, 1988a; Mahoney and Coffin, 1997a), therefore further justifying the idea that the anomalous behavior actually is represented by the present-day scenario. In fact, many other arguments can be used to support either the normality or abnormality of the processes that generate LIPs, all of which depend on the frame of reference that is being used. Consequently, it is suggested that a first step for avoiding mythical thinking in the study of LIPs is that instead of referring to "normal" and "extraordinary" or "abnormal" events when describing these provinces it is wiser to restrict our judgment to distinguish two types of volcano-magmatic activity without making reference to their status of "normality."

To avoid mythical thinking, the following step is to establish as objectively as possible the characteristics of each of the two identified types of volcano-magmatic activity. Although apparently simple, it is in the comparison between the two types of activity that the risks of recreating the processes of mythical thinking become very large. This is the case because a large number of sometimes unidentified assumptions might influence the form in which some evidence is presented and compared with the other extreme of the spectrum. For instance, one of the presumed distinctive characteristics of LIPs, until now, has been their high rate of magma production. Magma production rates, however, cannot be directly measured either in LIPs or in present-day volcanic provinces, as these processes take place in a part of the Earth that remains inaccessible for direct observation despite recent advances in technology. Consequently, any judgment concerning LIPs or any other volcanic province around the world that is based on magma production rates necessarily contains an underlying set of previous assumptions that are necessary to infer such magma production rate in the first place.

Understanding the role played by such underlying assumptions is critical to avoid a logical error during the process of inference that might result in the construction of a formal fallacy. As some readers might not be very familiar with the formal nomenclature of logic, it might be convenient to open a parenthesis in the presentation that is devoted to examining in more detail the various forms in which a fallacy can be committed. Readers familiar with such rules of the process of reasoning might skip this parenthesis.

Anatomy of a Fallacy

There are many ways in which formal errors in logical reasoning can take place. Some of these errors are somewhat difficult to identify, as the argument (or syllogism, in the nomenclature of logic) may seem to be correct at first sight, and these are generally referred to as fallacies (Copi and Cohen, 1994). One such error is to construct a categorical syllogism that gives the appearance of containing three terms (two premises and a conclusion) when it actually contains more. This error commonly takes place when one of the premises actually contains a second premise that is presented in a cryptic form, being embedded in the premise that is easily identified. Alternatively, this error can be made when a given premise is considered to have a fixed truth value when in fact its truth value depends on the truth value of another, non-explicitly mentioned premise. The exact name of the fallacy that is committed in this form depends on the definition of *syllogism* that is used. Nevertheless, these general groups of fallacies can be detected if proper attention is given to some simple rules.

In particular, it is noted that the use of an ambiguous statement as a premise in the construction of another syllogism may result in an error for three reasons (Copi and Cohen, 1994). First, an error in the syllogism is produced because the truth value of the ambiguous premise depends on a different premise. Consequently, failure of detecting such a cryptic premise leads us to commit the "fallacy of quaternio terminorum," or the fallacy of four terms (note that the name remains regardless of the real number of hidden premises). Second, if the truth value of one of the cryptic premises turns out to be false, then the conclusion of the second syllogism necessarily must be false. Failure in acknowledging this possibility will lead us to commit the fallacy of "drawing an affirmative conclusion from a negative premise." Third, failure to recognize the existence of the hidden premise might contribute to committing the fallacy of "equivocation" when one of the terms is used in different senses in each of the two premises explicitly stated in the syllogism.

To illustrate the three types of fallacies in a context relevant to the present chapter it is convenient to consider the form in which seismic imaging is sometimes used to make inferences concerning the characteristics of the Earth's interior, and how these inferences are sometimes used in connection with the origin of LIPs. Although some workers might consider seismic imaging of the Earth's interior an unbiased and very objective source of information, it turns out that there are several assumptions made in the interpretation of the actual data (for a recent and extensive discussion of such assumptions see, e.g., Thybo, 2006). Discrepancies concerning some of those assumptions can actually lead to discrepancies concerning the interpretation of the actual data in significant forms. Furthermore, regardless of the final interpretation concerning the probable occurrence of melt at depth that is reached when conducting a seismic survey of a region, it is clear that measured seismic data only contain information concerning the physical state of the rocks through which seismic energy actually traveled. If that physical state changes in time, then the conclusion reached by the seismic survey would be invalid. Realistically we do not expect that the physical state of large portions of Earth's interior will change in lapses of minutes or even of days, but if lapses of thousands or even millions of years are involved, however, then the occurrence of such a change becomes a real possibility. Therefore, it should be clear that seismic information only provides some constraints concerning the probable physical state of the Earth's interior at times not much different from that of measurement, and even in this case it is possible to reach two contrastingly different conclusions based on the same type of data, as illustrated by comparing the conclusions reached by Thybo (2006) with those reached by Priestley and McKenzie (2006) concerning the presence of melt within the mantle.

In the present context, the relevant fact is not to discuss which of those conclusions is "true" but to focus on the fact that completely different conclusions (either a "true" or a "false" conclusion in logical parlance) can be reached by using the same type of observations. The relevant part is therefore that the difference between the two possible truth values of the conclusion depends on the assumptions that are used for the interpretation of the observations. Consequently, although seismic interpretation might be a reasonable source of information, there is an ambiguity in its truth value, as this value depends on the truth value of the premises used in the interpretation of the signals. Consequently, failure in acknowledging the relevance of the assumptions made when interpreting seismic information facilitates the completion of the first type of fallacy (fallacy of four terms) as those premises become hidden and constitute a source of ambiguity that is not acceptable in a valid syllogism.

The second type of fallacy (drawing an affirmative conclusion from a negative premise) might be extremely difficult to identify because commonly we overlook the truth value of a premise that is not explicitly stated in the syllogism, and, even worse, the truth value of the hidden premise might become accepted "de facto" more as the result of habit than as the result of a real exercise of logical inference. Actually, this type of error is very common in mythical thinking, as it promotes the selective acceptance of some facts, rejecting any questioning about them, and many examples of this type of fallacy can be found in the literature dealing with the existence of mantle plumes in Earth, some of which were examined by Dickinson (2003).

A practical example of the third type of fallacy (of equivocation) in a context relevant for the discussion about the origin of LIPs can be found when the term *melt* is under scrutiny. For instance, some workers have argued that the amount of melt produced in a given setting can be inferred from the composition of the erupted products, and that such volumes of melt can be corroborated by using seismic signals (e.g., Korenaga et al., 2002; White et al., 1992, 2001). Despite their apparent appeal, these works have the problem of combining two disparate sources of information (seismic and geochemical), each of which has a different set of premises that may or may not be true, therefore resulting in two conclusions (one seismic and the other geochemical in nature) that are used as premises for a new syllogism despite the existing ambiguity in terms of each of their truth values. Actually, the source of the problem (at a logical level) is that the term *melt* in each of the original approaches has a slightly different sense. In the seismic study *melt* actually denotes *crustal thickness,* which in turn has been assumed to be the result of the collection of a liquid phase that (1) was extruded in its entirety from the region of origin but (2) remained trapped at depth to form the observed crustal thickness. In contrast, in the geochemical approach, *melt* denotes a "cumulative volume of liquid" that was formed within the region of origin before an eruption and that was expelled all the way to the surface. Therefore, when comparing seismic and geochemical evidence we are comparing the inferred thickness of a solid layer that we think was produced as the result of a complex process of melt extraction out of the region of genesis, but that nonetheless was not sufficient to move such liquid all the way to the surface to be later eroded, with an inferred volume of liquid that was expelled all the way to the surface. Evidently, many more factors were involved in the creation of the seismic "melt" than in the creation of the geochemical "melt," and any numerical agreement related to the volumes of "melt" produced in the two cases might be a coincidence rather than being a direct measurement of a given melt volume. Failure in recognizing this possibility, inherent to the slight change of meaning of the term *melt* in both methods, leads to the "fallacy of equivocation."

Before returning to the main subject of this chapter, it is important to note that identification of fallacies must not be confused with undue criticism to any of the methods used to make inferences concerning the internal state of Earth. For instance, although the conclusion reached in the sense that the agreement of both "thicknesses of melt" in the third example given above (i.e., one seismically and the other geochemically determined) gives place to a fallacy, such fallacy of equivocation does not allow us to make any judgment of truth concerning the validity of each of the methods if considered independently of each other. This is the case because the fallacy is actually formed when both types of information are forced to be part of the same syllogism, and not because any of the parts is necessarily false. In other words, it might be that the seismic method yields a true crustal thickness, whereas the geochemical method yields a true fractional distribution of melt as a function of depth, even if the former is not necessarily related to the volume of melt produced in a single region of partial melt (RPM) at a given short time interval, and the latter does not necessarily correspond with the estimated crustal thickness measured by seismic methods. Consequently, it should be clear that the use of both methods of obtaining information about some of the characteristics of Earth's interior will still be valid (at a logical level) as long as the conclusions reached by each method are not invoked as "corroborations" of the truth value of the conclusions reached by the other method.

As a summary of this parenthesis it can be said that if the set of assumptions made by any method of observation is not the same for the two types of volcanic activity being compared, then the comparison might be biased, and it might result in a fallacious conclusion. Consequently, a critical step that needs to be taken to avoid mythical thinking in relation to the origin of LIPs is to be certain that we are comparing the same type of evidence gathered through equivalent means and with the same set of underlying assumptions for both LIPs and non-LIP provinces. In the following sections I examine with some detail some of the commonly used sources of information, and the form in which these sources of information can allow us to compare LIPs and non-LIP volcanic provinces in a relatively unbiased form, starting by punctuating the meaning behind some key terms.

"CFBs" instead of "LIPs" and "Modern" instead of "Non-LIP" Volcanic Provinces?

One of the most pressing restrictions faced when attempting to characterize LIPs is that because of their various levels of exposure and ease of access not all of these provinces have been studied with the same detail. Consequently, it might be convenient to restrict the universe of studied provinces to those that can provide the most complete record of evidence obtained independently of any genetic interpretation (note that *universe* is used throughout this chapter in the mathematical-logic sense, particularly in set theory, where this term denotes the set that contains as elements all the entities described by the class). In particular, it is noted that among the best documented LIPs there is a group of provinces that have erupted most of their products over continental crust (continental flood basalts, or CFBs), and for which a flow-by-flow stratigraphy and a set of relatively extensive radiometric ages is available in many cases. As in all LIPs, CFBs are characterized by having large volumes of lava (>10^6 km^3) usually erupted in very short times (<1 m.y.) (Hooper, 2000). Consequently, we might consider that CFBs are good representatives of LIPs even when LIPs and CFBs are not completely equivalent terms (the latter being a subgroup of the former, regardless of which definition of a LIP is adopted).

On the other hand, characterizing the "non-LIP" provinces is not as simple as it might seem at first sight, especially if this type of province is defined by different criteria that do not become the complement of the "LIP" definition. Good candidates that can be considered to *represent* this type of volcano-magmatic activity are all of the volcanic provinces actively forming at present, because most geoscientists would easily accept that no LIP is being formed at present. It is emphasized that we are concerned with finding a group of provinces that can be considered as representative of the "non-LIP" type of activity, rather than defining the whole universe of provinces belonging to this group, and in this sense the "present-day" subgroup seems a good candidate. It should be noted, however, that not all of the present-day provinces have been studied with the same detail, that the amount and quality of available information might vary from province to province, and that "present-day" might be a far too restrictive time frame. For instance, although some direct observations allowing us to determine magma extrusion rates very precisely have been made in a few "present-day" provinces, these are restricted to a limited number of volcanoes. Furthermore, the period of observation available for some volcanoes in some cases might be extremely short to be considered as representative of the average behavior of that particular volcano. Consequently, it would be unwise to restrict this type of volcanic activity only to those examples where direct observation of an eruption has taken place. Thus, the second type of volcano-magmatic activity (the one that will be compared with CFBs) might be reasonably formed by "modern" volcanic provinces, understanding by this term all examples of relatively recent volcanic activity, regardless of whether they can be considered part of presently active provinces or not, provided that they cannot be considered akin to any LIP in an obvious form.

An advantage of comparing CFBs and modern volcanic provinces (as just defined) instead of the larger universe of LIPs and non-LIPs is that we allow ourselves to compare information gathered through the same methods in both instances. In other words, instead of being forced to compare information gathered through, say, seismic and geochemical methods, therefore risking the danger of committing a fallacy of equivocation (see above), we can compare both provinces by using information that is gathered by exactly the same methods. In this form we also diminish the possible bias that could be caused by committing the fallacy of four terms, because even when undoubtedly there might be hidden premises not explicitly stated in our analysis, those hidden premises will be shared by both groups entering the comparison. Consequently, no selective bias will enter our comparison, therefore diminishing the possibility of recreating the patterns of mythical thinking.

The only fallacy that cannot be completely eliminated from any analysis of a natural system is the fallacy of drawing an affirmative conclusion from a negative premise. As pointed out by Oreskes (1999, p. 3), "the history of science demonstrates that the scientific truths of yesterday are often viewed as misconceptions, and, conversely, that ideas rejected in the past may now be considered true." Actually, this condition is inherent to all natural systems, because a definitive proof is only possible in closed systems. In all open systems positive proof is not possible, and we are limited to eliminate alternative hypotheses only by disproving them as new evidence becomes available (Oreskes et al., 1994). For this reason, extrapolation is a procedure that always has the possibility of leading to a fallacious syllogism. Evidently not all of the extrapolations are fallacies, but it is extremely important to be aware at all times of the original range for which factual observations were used as well as of the assumptions behind the extrapolation. In this sense, while there are many advantages in reducing the universe of LIPs to the representative group of CFBs as discussed above, there is also an increased danger of drawing a fallacy when conclusions reached by studying CFBs are extrapolated to other LIPs. Evidently, the larger the differences between a given LIP and the bulk of CFBs, the larger is such a danger. For instance, although there is no doubt that giant dike swarms (GDSs) or Archean greenstone belts (AGBs) might have all the requirements to be considered LIPs, there are significant differences between these types of provinces and the group represented by CFBs. In contrast, the differences between many oceanic plateaus (OPs) and ocean basin flood basalts (OBFBs) on the one hand and CFBs on the other are probably not that significant. Therefore, the danger of a fallacy will be larger when interpreting GDSs and AGBs than when interpreting OPs or OBFBs. In consequence, it would seem that from the point of view of logical reasoning it is convenient to have criteria that could be used to distinguish between these types of LIPs in the classification scheme. Similar arguments can be used to sustain a case of fallacious reasoning when extrapolating conclusions reached by using the subgroup of modern volcanic provinces to other, more ancient "non-LIP" provinces. Nevertheless, if we compare the benefits of reaching some insights into the processes by comparing representative subgroups of each type of volcanic activity, rather than comparing the whole universe of provinces forming each group, the danger of extrapolation becomes justified.

In summary, it should be clear that by adjusting our universe of observations to a range that allows us to have equivalent sources of information across a given threshold, the danger of committing a formal fallacy is reduced. This also should help us to eliminate the more unlikely hypotheses much more easily, because the number of parameters entering our analysis is also likely to be reduced. The problem is then to decide which of the proposed criteria entering the definition of a LIP lead to more significant thresholds that can be used to make a significant distinction between LIP and non-LIP types of volcano-magmatic activity in genetic terms.

TOWARD AN UNBIASED YET USEFUL CLASSIFICATION SCHEME OF LIPs

Reducing the universe of examples that need to be considered when trying to establish the main differences between LIPs and non-LIPs, as done in the previous section, is an important step in avoiding biasing the analysis, and at the same time ensuring that we have a large enough number of examples that can be considered as representatives of each group of contrasting volcano-magmatic activity. To really avoid the most frequent fallacies, however, it is necessary to examine with some care the actual information that will serve as the basis for the intended comparison to be sure that we are actually comparing equivalent types of information (or in the language of logic, to be sure that we are dealing with the same number of premises in each case). One of the parameters suggested both by Sheth (2007) and by Bryan and Ernst (2008) is to consider whether the province is characterized by intrusive or extrusive rocks. Nevertheless, although Sheth (2007) uses this parameter as a foundation for establishing his hierarchical classification, Bryan and Ernst (2008) only use it to distinguish different types of provinces that are at the same hierarchical level. It is considered here that a hierarchical classification that explicitly distinguishes between predominantly extrusive and predominantly intrusive LIPs provides a natural breakpoint in the continuum of volcano-magmatic activity, and consequently this criterion seems to be well justified as an integral part of the classification scheme of LIPs.

Among the other parameters that have been proposed to enter the definition of a LIP there are four that can be directly measured without the need to make reference to any genetic model, and also requiring a lower amount of previous assumptions. These parameters are (1) the age of the rocks, (2) a time lapse of activity, (3) the area covered by the rocks, and (4) the volume of igneous rocks. A fifth, relatively unbiased parameter that can be obtained from those direct estimates is an average time of activity. Although undoubtedly there are uncertainties concerning the estimation of all of these parameters in every type of volcanic province (i.e., LIPs and non-LIPs alike), when all things are considered these uncertainties do not exert any influence in the validity of the inferences made from the perspective of logical reasoning. Nevertheless, their potential value to yield a significant classification scheme is not the same in all cases. These parameters will be examined in more detail next.

Age of the Province

Both the age of the province and the time lapse of activity commonly are determined from radiometric measurements made on the rocks of that province. Whereas definitively the uncertainties are not the same for each radiometric method available, from the point of view of logical reasoning all of the different methods are completely equivalent because the type of assumptions made by all of them are essentially the same (e.g., the system remained closed to mass transfer of a given isotope after formation of the rock, the decay rates are well known, the contents of the isotopes of interest can be determined accurately, etc.). Consequently, despite the fact that the numerical uncertainties can change depending on the method used to obtain the date (and this in turn might depend on the age of the rocks themselves), all radiometric ages can be considered as completely equivalent sources of information at a logical level. Therefore, in these two cases we can discuss the relevance of the parameters measured without concern about the specific uncertainties associated with the method of measurement.

Although at present some questions need to be addressed in which the age of the various LIPs might be important; e.g., links with exogenic or terrestrial forcing processes or mass extinction events, periodicity, and clustering of LIP emplacement (see references in Ernst et al., 2005) there does not seem to be a significative difference in the genesis of older versus younger LIPs that can be identified from other data. For instance, a plot of the age against the area of LIPs does not reveal any particular trend (Fig. 1). Although this plot does not include a few LIPs with a documented extension larger than 10^5 km^2, the exclusion of these data does not alter the absence of a pattern. Also, the fact that the age used to plot the data was always the oldest age in the database should not modify this conclusion, because some of the reported

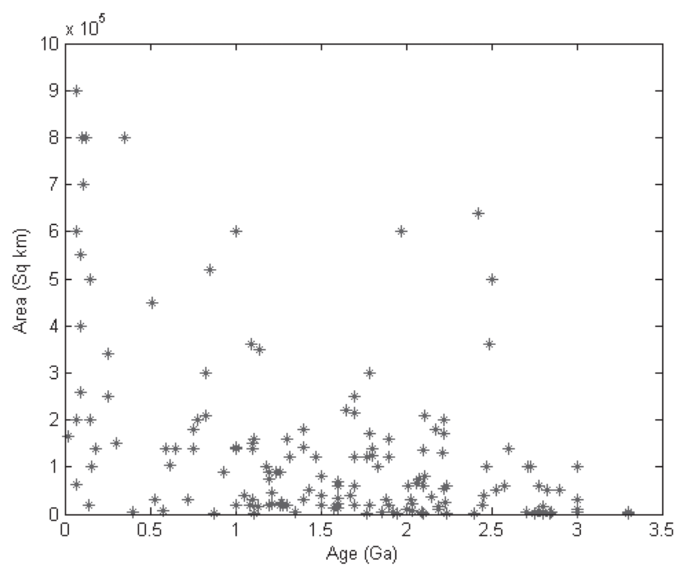

Figure 1. Plot showing the age versus the area of LIPs for which determinations of both variables have been reported in the database of the Large Igneous Provinces Commission (accessed May 2010). Exclusion of five LIPs for which the area exceeds the limits on the vertical axes of the figure does not change the absence of any trend, and actually makes it more difficult to observe the scatter of the data shown in this figure.

age ranges are very small relative to the total age scale of the figure. Thus, at least at present, it would seem that using the average age of the province as a parameter in the classification scheme does not provide any advantage from a genetic point of view.

Duration of Activity

Perhaps the biggest difference in the definition of a LIP proposed by Sheth (2007), relative to those of Coffin and Eldhom (1992) and Bryan and Ernst (2008), is that Sheth's definition does not consider the duration of activity as an important parameter. Because we are interested in a classification scheme that can be used to obtain an insight into the genesis of these provinces, and considering that given enough time any province might reach dimensions that would classify it as "large," as pointed out by Bryan and Ernst (2008), it would seem that contrary to Sheth's suggestion, the duration of activity is a parameter that should enter the definition of a LIP at essentially any hierarchical level. Failure to include this parameter might result in ambiguities even in the most basic definition of a LIP. To illustrate this point, consider that although the Hawaiian-Emperor Seamount chain can be included as an example of a LIP if only size is considered, this requires the inclusion of products of the Meiji Seamount that were erupted >80 m.y. ago, and probably extending to more than 100 Ma (Scholl and Rea, 2002). Such a time frame exceeds the limits introduced in the definition of a LIP made by Bryan and Ernst (2008), and therefore the whole chain of seamounts should not be considered a LIP even when it is probable that such chain has been created by essentially the same process. Evidently, we could impose the constraints on the time of activity as set by Bryan and Ernst (2008) and split the seamount chain into LIP and non-LIP parts, but this would seem a rather arbitrary breakpoint that has nothing to do with the genesis of the province. Furthermore, if the chain of seamounts is split in time intervals, each of 5 m.y. (note that this continues to be an arbitrary time lapse without any other apparent justification behind it), we would conclude that the most recent LIP in the chain is the most productive, which in turn leads to another series of problems concerning the presumed plume head and tail production, as already discussed by Foulger (2007). Perhaps a more natural breakpoint in this case would be to consider the time scale associated with the formation of one individual island, as this period is more likely to represent a pulse of volcanic magmatic activity. Evidently, if only the more recent volcanoes of this chain (say, ca. 1 Ma) are considered as part of the province, instead of considering the whole volume of the chain of seamounts, we would need to consider the volume of one of the islands. Note that the 1 Ma breakpoint selected here is slightly larger than the interval of formation of the Big Island of Hawaii, because the oldest volcano of this island (Kohala) seems to be younger than 0.78 Ma (Sherrod et al., 2007), but such a difference does not alter the following conclusion because the volume of products is much smaller than the normally accepted threshold values in either definition of a LIP. A representative volume of the Big Island can be obtained by considering a circular cylinder having the same basal surface than the present-day island of Hawaii, ~10,500 km^2, and a height of 9 km that would account for the submerged part of the island that nonetheless is over the seafloor. Both in terms of the surface area and the associated volume, it is clear that the island of Hawaii should not be considered as a LIP because both area and volume are about one order of magnitude smaller than the accepted thresholds; this remains to be the case even if the much lower threshold set by the LIP definition of Sheth (2007) is used. Therefore, as illustrated by this example, the time used as reference is extremely important to define whether a given province can reach the required size (whether areal extent or estimated volume) to be considered a LIP. On the other hand, this example also illustrates that selecting an arbitrary threshold for time in the definition of a LIP can lead to an unjustified segmentation of a province that could mask relevant clues concerning the genesis of these provinces.

Another set of problems is derived from the fact that we would need to decide which time scale is really significant in a LIP classification scheme if we want to assign the status of a hierarchical marker to this parameter. For instance, we might decide to include in our estimations the oldest and youngest available radiometric ages for one particular province, because there is no doubt that radiometric determinations are unbiased in terms of any genetic interpretation of the provinces. Adoption of the radiometric record in this form, however, would imply neglecting information coming from detailed stratigraphic or morphologic studies that suggest that extremely long periods of quiescence might have occurred in at least some of the CFB provinces (Jerram and Widdowson, 2005). Therefore, by adopting the radiometric age range without considering the local stratigraphy, we risk estimating an extremely large period of activity that might not convey an accurate representation of real processes occurring in the province at any time. At the other extreme of the temporal scale, we could consider the possibility of estimating the time of activity as reflected by one eruptive event, and with enough information in assessing typical times of quiescence. This approach faces a practical problem, however, that precludes the real application of this criterion in a deterministic form. The problem is that we do not have the resolution power to date with radiometric means and with the required accuracy the products of a single eruptive event. This lack of resolution is associated with the probable fact that most eruptive events take from less than a day to less than ten years to be completed (Simkin and Siebert, 2002). Thus, even when the direct observation of active volcanoes tells us there is the occasional eruption that might last over 20 yr, it is really risky to extrapolate such long durations as typical values for eruptions taking place in LIPs. Consequently, it is clear that obtaining a really accurate estimate of the real time of duration of any single eruption observed in the geologic record is almost impossible at present, and therefore it would not be recommended to use this time frame as the basis of a hierarchical classification of LIPs.

In summary, the exclusion of a time frame in the definition of a LIP seems to introduce an unwanted source of uncertainty that hampers the identification of significant trends in a genetic interpretation of LIPs, but uncertainties in the determination of relevant time frames preclude the use of this parameter as a marker that can be used to define a hierarchical category in the classification scheme. Consequently, whereas it is recommended that the duration of activity be included in the definition of a LIP, this should be done with extreme care, keeping in mind that at least two time scales might become important in further analysis. One of these time scales is related to the whole duration of activity in the province; the other is related to the probable duration of individual events. The first of these relevant time scales formed part of the original definition of a LIP and therefore has been incorporated by most studies made on the subject in the past 15 yr. In contrast, the second of these time scales has been excluded from the analysis of the evidence in most cases. The relevance of such a time scale will be further discussed later in this chapter.

Area and Volume of Erupted Products

Sheth (2007) considered that the area covered by igneous rocks in a given province should be used instead of using their volume as a parameter required in the definition of a LIP. The justification for this preference was that estimation of volumes are more uncertain and are affected more than areas by erosion in the older provinces. Although undoubtedly it is certain that the volumes of igneous rocks in LIPs must include uncertainties derived from their old age and tectonic influences, it is also true that measurements of erupted volumes in modern volcanic provinces are not devoid of difficulties. Actually, from the point of view of logical reasoning, the fact that such uncertainties in the estimation of volumes does increase with the age of the province is irrelevant, because such uncertainty will influence the position of the threshold value, but it does not affect the fact that this parameter can be used to define such thresholds. For instance, some of the uncertainties found when estimating the volumes of erupted products in modern volcanic provinces include the burying that results from still more recent products as well as some important effects of erosion. In addition, the lack of continuity in the exposed products of either CFBs or modern volcanic provinces makes both types of provinces equally susceptible to spurious correlations based on geochemical arguments (if the regional source of magma is more or less homogeneous) or paleomagnetic arguments (if two different eruptions took place either in a relatively short time period or at two very different times that nonetheless had similar orientations of the paleomagnetic field). Consequently, the possibility of committing an error of judgment that could affect the true value of a particular premise (or in this case the number associated with the volume of erupted products in each province) is essentially the same in both CFBs and modern volcanic provinces, and therefore it does not result in a selective bias. Relatively similar arguments can be used to extrapolate this result to the realm of other LIPs, although in this case the uncertainties in the isotopic ages can also become important sources of spurious correlations.

On the other hand, it would seem that volume can bear a more direct relationship than area from the point of view of genetic processes. The area covered by some erupted products might depend strongly on factors such as previous topography or vent distribution, but it also might depend on the viscosity of the magma, the mechanism of growth of the products (endogenous versus exogenous), and rate of eruption. Undoubtedly, topography and vent distribution are also likely to influence the estimation of volumes of igneous rocks, but all the other parameters will have less influence in those determinations. Besides, the volume of igneous rocks can be related (directly or indirectly) to the amount of magma produced in a given part of the mantle, which is likely to bear some information concerning the genesis of those provinces. Consequently it is considered here that volume is a better parameter to be used for the characterization of the size of any province than area. Other reasons to prefer volume over areal coverage were examined elsewhere (Bryan and Ernst, 2008).

Although these considerations indicate that volume is indeed a required parameter that needs to be included in the definition of a LIP, it remains to be determined whether this parameter can be used to establish a finer classification of the products (i.e., as a hierarchical indicator). At this time it seems that such finer division might not be possible because the number of provinces for which volume estimates are documented is relatively small. In effect, most of the provinces included in the database of the Large Igneous Provinces Commission (accessed May 2010) at the time of this writing lacked this estimate of their size. Consequently, identification of significant breakpoints in volume estimates for the whole universe of LIPs would seem premature. In addition, it should be noted that some of the volume estimates are somewhat speculative in terms of the relevant ages involved, especially in those cases when the volume estimates have been based in indirect observation through geophysical means. As an example, it is interesting to note the case of the Okavango dike swarm in Botswana. Jourdan et al. (2004) documented the presence of two populations of dikes of contrastingly different radiometric ages in this dike swarm, suggesting that the younger, Early Jurassic dikes were emplaced along a reactivated zone of lithospheric weakness marked by the older, Proterozoic dikes. From this evidence it is clear that the combined volume of all of the dikes in the swarm is an overestimation of the real volume of magma involved in the formation of a single LIP. Furthermore, as pointed out by Jourdan et al. (2004), the presence of two contrasting ages in dike swarms might not be unique to Okavango, making unclear what proportion of any swarm has been emplaced as the result of a unique event of LIP dimensions, or rather it contains dikes emplaced during two events separated in time for more than 50 m.y. (which is the time frame specified in the definition of a LIP by Bryan and Ernst, 2008). Consequently, any fine subdivision of LIPs based in volume as a criterion would be somewhat misleading at this time, and therefore the volumes of whole provinces should enter the definition of a LIP only as a rough indicator that would allow us to divide the continuum of volcano-magmatic activity in two categories: “Large” and “no-Large” provinces. Considering the uncertainties associated with the quantitative determination of this parameter, it seems that discussions concerning the exact location of the breakpoint dividing both categories are somewhat useless at this time.

It was noted above that there are two broad time scales that should be kept in mind. The situation with the volumes of igneous rocks is not different. In the preceding lines I have examined the relevance of volumes of LIPs regarded within the entire province. However, a different form of comparing volumes of igneous rock is to consider the products of single eruptive events. In this comparison it might be useful to use data from the representative provinces of each end member as defined above (i.e., CFBs and modern volcanic provinces) rather than attempting a comparison drawing examples from the whole universe of LIPs and non-LIPs. In the case of a typical modern volcanic province the volume of extruded magma during one single extrusive event can be considered to be ~<0.5 km^3, having as a typical upper limit that portion extruded during an eruption with a volcanic explosivity index (VEI) of ~5. Nevertheless, it is noted that although very seldom, the volumes extruded in this type of provinces might achieve much larger values, as exemplified by the 15 km^3 associated with the Laki eruption of 1783 (Pyle, 2000). For CFBs, the volumes involved in a single extrusive event are also variable, as revealed by the data compiled by Tolan et al. (1989) for the Columbia River Basalt Province. These data, shown in Figure 2, indicate that a large proportion of single eruptive events involved relatively small volumes of magma, having a mean value of ~60 km^3. More voluminous events (~750 km^3) have also been documented, although these are a very reduced proportion in terms of their frequency of occurrence. Finally, the data in this figure show that a still lower proportion of events might have record values of volumes exceeding 2000 km^3. Thus, even when only in a rather approximate form, a difference of two to three orders of magnitude might seem to distinguish both provinces at the scale of the volume of individual eruptions. As will be argued below, this form of comparing sizes of different types of volcano-magmatic activity contains important clues from a genetic point of view that are not easy to identify when comparing total volumes of erupted products in the various provinces, as has been commonly done in the analysis of LIPs until now.

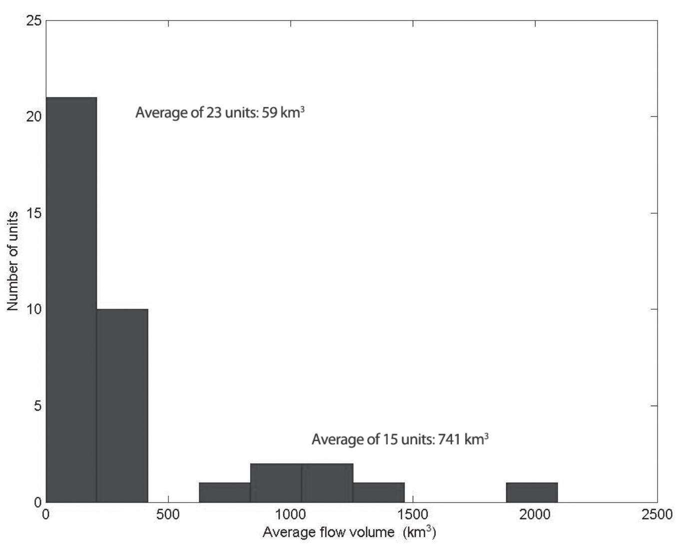

Figure 2. Histogram showing the volumes of individual lava flows in the Columbia River Basalt Province (data from Tolan et al., 1989).

Eruption Rates, Magma Production Rates, and Magma Volumes

Another parameter that has been suggested to be critical for the correct definition of a LIP is the rapidity of emplacement of at least a significant part of the province. Although the potential for committing a fallacy by including the intrusive part in the comparison of CFBs and modern volcanic provinces was pointed out earlier, it is necessary to examine in more detail the form in which eruption rates, magma production rates, and magma volumes relate to each other in order to better appreciate the extent to which these parameters might influence the definition of a LIP, promoting a bias in the analysis of observations. First it is noted that unlike the volumes of erupted products and the associated extrusion rates, the volumes of magma and magma production rates in volcanic provinces cannot be measured directly. The fact that we deal with factors requiring additional assumptions for their estimation increases the risk of committing a fallacy because the number of premises is increased as well as the chain of associated syllogisms. Furthermore, although it might be tempting to consider the calculated average extrusion rate as directly representative of the magma production rate of a volcanic province, it is important to be aware that such an association is incorrect and might favor the unnoticed introduction of a strong bias in the form in which we envisage both types of activity. This is better appreciated if we consider the diagram of Figure 3. In this figure the volume of melt stored in a region of partial melting (RPM) is plotted as a function of time for several situations. A constant rate of magma production without any event of extrusion results in the discontinuous line drawn from t0 to t6, whose slope is the specified rate of magma production in this case. If periods of melt tapping are allowed to exist while magma production continues to take place at the same rate, the amount of melt available at any time in the RPM will no longer be indicated by the discontinuous line, but rather it will be indicated by the solid line with different slopes. The changes in the slope of this line found in the intervals t1–t2, t3–t4, and t5–t6 are associated with tapping events E1 to E3, respectively, displayed at the lower part of the diagram. E1 is a tapping event that has a rate equal to the magma production rate. Consequently, during the time interval t1–t2 the volume of melt produced in the RPM is effectively canceled out by the volume of melt tapped out, therefore resulting in the lack of melt accumulation in the RPM during this time. Thus a tapping event like this one might yield the impression of a period of zero magma production. As the tapping event comes to an end at t2, the curve of melt volume resumes its previous trend, yet the volume of magma

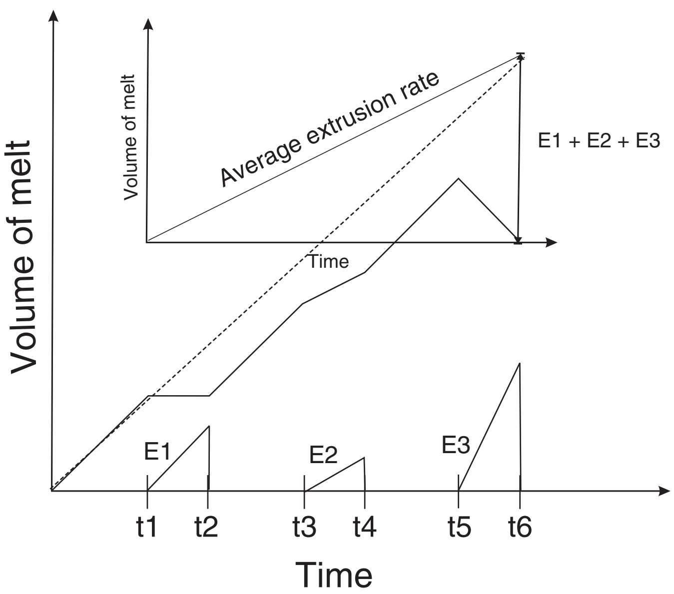

Figure 3. Plot showing the general relationship between magma production rate, volume of magma stored in a given region of partial melt (RPM), and magma tapping events. See text for details.

in the region of melting is smaller than it would have been if no tapping event had occurred. A new tapping event initiating at t3 again influences the slope of the curve representing the melt volume accumulated in the RPM. For illustrative purposes, in this case the tapping rate is set to be smaller than the magma production rate. The disparity between magma production and magma tapping rates causes the magma volume in the region of partial melt to keep increasing between times t3 and t4, despite the occurrence of the tapping event. Again, it is remarked that in this case the real magma production rate was actually the same as it was before the occurrence of E2, yet the apparent magma production rate obtained from the slope of the curve marking the melt accumulation is smaller. Once again, as the tapping event comes to an end, the slope of the curve representing the amount of melt in the zone of storage resumes its original value. The tapping event starting at t5 has a tapping rate faster than the magma production rate. During the interval t5–t6 the melt content in the region of partial melt will decrease, even if during this time the rate of melt production remains unaltered. Thus, even when physically there is some melt being produced during this time, the magma production rate would seem to be negative because the total melt volume stored within this region does not increase but effectively decreases with time. Evidently a tapping event like this one cannot continue indefinitely, because the melt in the RPM will eventually be exhausted. In consequence, this type of tapping event is limited by the amount of magma previously accumulated in the RPM rather than by the magma production rate itself.

Although highly schematic, the various situations depicted in Figure 3 illustrate several important aspects concerning the relation between magma production rate, magma tapping or extrusion rate, and magma volumes. In particular, this diagram shows the dangers of estimating a magma production rate with data that strictly belong to magma extrusion rates, even if all of the magma extruded from the region of melting was accurately measured at the surface. First, the diagram shows that a variety of extrusion rates can be supported by a single value of the magma production rate. Second, extrusion rates faster than production rates are sustainable only if there is a time gap between the moment of initiation of magma production and the initiation of the extrusive event; the larger this gap, the longer the interval with a high extrusion rate can be sustained before exhausting the melt available for extrusion. An alternative form to visualizing this is that a situation in which magma is extracted from the RPM as soon as it is formed is not capable of sustaining a large extrusion rate. Third, although the cumulative extruded volumes can be used to calculate something that could be interpreted as an average magma production rate (light axes at the top of the figure), the slope of this curve does not necessarily represent the actual magma production rate, because in fact we ignore the exact moment when magma started to be produced (i.e., t0 is not equal to t1, the time of the initiation of the first eruptive event). Fourth, the total volume existing at a given time at depth cannot be determined from information concerning the volume of erupted products. Fifth, even very slow production rates may sustain large rates of extrusion, given the adequate time for magma accumulation. Sixth, if we disregard the presence of the extrusive events and somehow are able to examine the solid line of the diagram, we would conclude that the magma production rate actually changed at t1, t2, t3, etc., because these points mark a shift in the slope of the melt volume content as a function of time, when in fact the figure was constructed by having a fixed value of magma production rate throughout all of the interval. Thus, this figure shows that even if we know accurately a magma extrusion rate we can say very little concerning the actual magma production rate at a given time. As a general corollary, it should be clear that much care should be exerted when interpreting the actual observations in attempting to characterize any volcanic province. For this reason, it is concluded here that magma production rates are not a good source of unbiased information, and that therefore such a parameter should be avoided when attempting to compare the volcanic activities forming CFBs with those of modern volcanic provinces, or to assess any genetic models proposed for LIPs as a whole.

Figure 3 makes reference to an extrusion rate, which to some extent can be considered equivalent to the emplacement rate of an igneous province. In the strictest sense an “extrusion rate” as used in this figure, however, only concerns processes taking place in the region of genesis of the igneous products, but once the magma is extruded from such a region it may be emplaced as an igneous intrusion, or alternatively it may be emplaced as a volcanic rock. The ability to identify the conditions favoring either of these alternatives remains a challenging subject of modern volcanology and is beyond the scope of this chapter. Actually, taking into consideration the uncertainties concerning the real age of the events leading to the emplacement of many intrusive rocks, as exemplified by the Okavango dike swarm mentioned above, the results are extremely uncertain when trying to establish significant breakpoints in the estimation of rates of emplacement of any province formed predominantly by intrusive components unless they have been exposed by erosion and have been extensively dated (which is seldom the case). Although estimates of the age of eruptive products are also relatively insufficient for many volcanic provinces, some of the correlations made for these types of products are relatively more certain than for intrusive rocks. Nevertheless, we might assess the value of adopting rates of eruption as a parameter, entering the formal definition of a LIP and its probable use as a marker in a better classification scheme. Again, this can be better achieved by restricting ourselves to examining information gathered from CFBs and modern volcanic provinces rather than by using the whole universe of LIPs and non-LIPs.

Although some variations can be found when comparing results obtained from two different CFBs, the accuracy obtained in radiometric ages of many of these provinces leads us to consider that extrusion rates during the peak of activity might have exceeded 100 km^3/yr in some extreme cases (Coffin and Eldhom, 1994). The same information, however, indicates that extrusion rates of CFBs are more commonly in the range of half a cubic kilometer to a few tens of cubic kilometers per year (Coffin and Eldhom, 1994), i.e., at least one order of magnitude smaller than the "extreme" cases. On the other hand, the rate of extrusion of modern volcanic provinces typically quoted even for the most productive volcanoes such as Kilauea and Mauna Loa are <0.05 km^3/yr, (Lipman, 1995). However, as pointed out by Harris et al. (2007), the exact definition of an *effusive rate* has been a source of confusion until recently, and much variability can be found in the reported values from the use of various measurement methods (note that the problems described by Harris et al., 2007, are an example of fallacies of equivocation, because the same term is used in slightly different forms in each case). When proper attention is given to the various sources of potential errors (note that the list of factors suggested by these authors to eliminate the fallacies are but three different forms of saying that all terms used in the construction of the syllogism should have an uniform meaning), the data shown by these authors indicate that extrusion rates in modern volcanic provinces are in the range of 0.01–1 km^3/yr, which might be more than one order of magnitude larger than the limit associated with Kilauea. In any case, the relevant point in the present context is to show that if one decides to compare CFBs and modern-day provinces by using the high end of the reported range of extrusion rates for CFBs (>100 km^3/yr) and the lower end of the range of modern volcanic provinces (<0.05 km^3/yr), the difference between both types of volcanic activity is strikingly large. If attention is focused on the other extremes of both ranges (0.5 and 1 km^3/yr for CFBs and modern provinces, respectively), however, it turns out that the difference between both types of activity is not that large. Furthermore, it could be concluded in the latter case that extrusion rates in modern volcanic provinces are actually higher than in CFBs. Consequently, acceptance of the first comparison and denial of the second constitute a clear example of selective focusing on information that yields a result expected because of a previously accepted notion of an extraordinary character of CFBs.

Interestingly, it has been documented that the extrusion rate for the Laki eruption of 1783–1785 might have reached a peak value of 8.7×10^3 m^3/s (Thordarson and Self, 1993). This value is equivalent to >274 km^3/yr, which is comparable to even the highest extrusion rates calculated for the more productive LIPs. From a morphological point of view, it has been documented that although a large variety of volcanic styles and architectures are found in CFBs, pahoehoe flows are not uncommon in these provinces (Jerram and Widdowson, 2005). This morphological type of lava seems to be favored by eruption rates <100 m^3/s (Griffiths and Fink, 1992), which are equivalent to just 3.2 km^3/yr, corresponding to the higher end of the range commonly accepted to be typical of modern volcanic provinces. In addition, it has been documented that the rate of arrival of magma to the crust in CFBs may be similar to that documented to occur in mid-ocean spreading ridges when large enough time intervals are considered (Macdougall, 1988b; Thompson, 1977). Nevertheless, these results tend to be dismissed without further examination, despite the fact that all of them would seem to suggest that the case for extraordinarily large extrusion rates in CFBs might not be as clearly established as commonly assumed. This attitude toward such lines of evidence contradicting the expected result is typical of mythical thinking and provides further support to the conclusion that a selective comparison between CFBs and modern volcanic provinces has been made in many instances.

In any case, the analysis made until now in this section indicates that "rapidity of emplacement" is a parameter that can be understood in many different forms. Consequently, this parameter should be used with extreme caution when attempting to distinguish between LIPs and non-LIPs. Most importantly, "rapidity of emplacement" must not be confused with "fast magma production rate," because the processes described by both terms are entirely different. Furthermore, although available evidence might seem to support the notion that LIPs are characterized by having erupted relatively large volumes of magma in relatively small periods of time, the rate of eruption of individual events in these provinces might have been not much different than the rate of eruption of individual events in other provinces. Therefore, the term *rapidity of emplacement* should be used to describe the formation of the whole province without extrapolating this term to the description of individual events. Actually, recognizing the possibility of having relatively uniform rates of eruption across the universe of igneous provinces constitutes a clue that could be significant when attempting to interpret the available evidence in genetically oriented models, as will be shown in the last part of the paper.

Tectonic and Crustal Settings and Geochemical Composition of Rocks

Among the list of parameters that were considered critical for the definition of LIPs by Bryan and Ernst (2008), we find tectonic and crustal setting as well as the composition of rocks. According to these authors, in order to be considered a LIP an igneous province should have been formed remotely from contemporaneous plate boundaries, in stable crustal regions with long histories of no prior deformation or contractional deformation, or undergoing extension, and with an "intraplate" geochemical signature. As these authors noted, some LIPs seem to have been emplaced near the edges of Archean cratons (Anderson, 1994). Although these settings might be defined as "intraplate" because of the distance to contemporaneous plate margins, nonetheless such regions represent areas that were undergoing extension at the time of LIP emplacement. Determining whether such extension was the cause of the LIP or vice versa has been one of the most debated subjects of the LIP literature over the years (Sheth, 1999a, 1999b). Consequently, adopting an evidently ambiguous indicator as a crucial part of the definition undoubtedly favors the selective interpretation of observations. Furthermore, as also noted by Bryan and Ernst (2008), "an intraplate tectonic setting is particularly problematic for the Cenozoic LIPs of North America." Nevertheless they dismissed such peculiarity by invoking the distinctive characteristics of these provinces in terms of their extent (including both area and volume) and rapidity of eruption, among other things. In other words, the really critical observations in this case would not be the tectonic setting but actually the other parameters. Consequently, arguing that the intraplate character of a province is critical for its classification as a LIP is a contradictory statement.

Concerning the composition of the rocks that form a province, it is noted that although there is the common perception that LIPs are remarkably homogeneous, a detailed examination reveals significant compositional variation taking place both spatially and temporally (e.g., Jerram and Widdowson, 2005). Furthermore, associating a "distinctive intraplate geochemical signature" to any rock type might involve a significant amount of circular reasoning (Anderson, 2000), which is another type of fallacious argument. Consequently, if the definition of a LIP is to be useful for providing an unbiased grouping of common features that aim to identify real patterns or trends of a given property, it would seem better to avoid including the geochemistry of the rocks in a province as a critical argument.

Finally, concerning crustal setting, Bryan and Ernst (2008) noted that the difference between silicic and other continental mafic-dominated LIPs is thought to be the crustal setting. Although such a distinction might justify the broad and genetically unbiased scheme dividing provinces based on the dominant composition proposed by Sheth (2007), it is uncertain whether such a subdivision of provinces based on this parameter can provide clues concerning their genesis without entering discussions concerning whether there is a "distinctive geochemical signature" for each setting. For this reason, it is considered here that although inclusion of this parameter in a classification scheme of LIPs in the form made by Sheth (2007) is acceptable, assigning a higher hierarchical value to such a parameter might increase the chances of falling into the realm of mythical thinking. Consequently, it would seem better to exclude this parameter from the list of critical ones, at least until more information becomes available.

How Many Parameters Are Needed to Create a Significant Classification of LIPs?

The analysis made throughout this section indicates that distinction between the intrusive and the extrusive components of a LIP is an important criterion that can help us to avoid unwanted fallacies in the interpretation of other characteristics of these provinces. Consequently, the first hierarchical level of the classification scheme proposed by Sheth (2007) seems to be well justified. Two other parameters that need to be included in the definition of LIPs are size (whether area or volume) and time. These two parameters need to be considered simultaneously in order to make a useful discrimination between LIP and non-LIP types of volcano-magmatic activity, but the available evidence does not seem to grant their use as hierarchical markers that can be used to construct a classification scheme with finer subdivisions at this time. Furthermore, it was noted that "rapidity of emplacement" is a somewhat ambiguous term that can be interpreted in various alternative forms, each leading to different interpretations. The more useful of such interpretations is when this parameter is used to describe the time of emplacement of one extrusive province. Thus size, time of activity, and the resulting rate of emplacement might be useful at present only to broadly distinguish LIPs from non-LIPs. Nevertheless, noting that emplacement rates of individual eruptive events can be similar across many types of igneous provinces might provide important clues in a genetic context. These clues will be explored with more detail in the following sections. The other criteria analyzed (age, crustal and tectonic settings, and the dominant composition of the rocks in the province) do not seem to play a crucial role in such LIP versus non-LIP distinction. Actually, these parameters might favor the occurrence of fallacious arguments when analyzing the observations. Consequently, they are not considered critical elements of the definition of a LIP in this work.

AN ALTERNATIVE MECHANISM OF FORMATION OF CFBs: THE VOLCANIC SYSTEMS APPROACH

As mentioned in the introduction, the definition of a LIP advanced by Coffin and Eldhom (1992) was highly influential in determining the orientation of much of the research done on the subject for slightly more than 15 yr. Perhaps the aspect in which this influence has been stronger has been in the association of LIPs with events of extraordinary character, implying with this that such provinces should be created by mechanisms entirely different than those operating in the formation of other provinces without the LIP characteristics. In particular, essentially all of the current explanations for the genesis of these provinces have always invoked the need for the *rapid production of magma* to explain the formation of LIPs. In the analysis made in the previous section, however, it has been shown that this perception is incorrect to the extent that little can be said about magma production rates by observing magma extrusion rates (Fig. 3). Furthermore, it was shown that determining the volume of an intrusive suite and assuming that all of that volume was emplaced almost coevally also could be unjustified in some cases, and that such presumption could lead to a fallacious estimate of the relevant magma extrusion rate. In addition, the previous section also presented some evidence suggesting that the rates of extrusion of individual eruptive events could have been similar both in LIP and non-LIP provinces, further supporting a perception of a LIP as the result of essentially the same underlying principles that control the formation of other volcano-magmatic provinces with no-LIP characteristics, rather than being the product of extraordinary processes.

Conceiving LIPs as the result of similar mechanisms than those underlying the formation of non-LIPs is not the same as saying that there are no differences between those two types of volcano-magmatic provinces. Actually, much of the analysis of the previous section was oriented toward identifying some parameters that could help us to identify breakpoints in the continuum of volcano-magmatic provinces that could be used as guides when attempting to unravel the details leading to the genesis of all of those provinces. This approach seems to have been successful, because it allowed us to identify an important clue that seems to have been overlooked until now. This particular clue is the observation that eruption rates of individual events might have been similar across all the universe of volcano-magmatic provinces, despite the undeniable differences in the volumes extruded when time intervals between 1 and 5 Ma are considered. The model developed in this section was constructed with this important clue in mind.

Based on the relationship that should exist between magma production rate, magma volume stored within the region of melt genesis (hereafter referred to as the region of partial melt, or RPM), and the rate of extrusion schematically illustrated in Figure 3 and described with more detail above, it becomes evident that one possibility for explaining the formation of LIPs while having an extrusion rate not that different from the extrusion rate of non-LIPs is to have a large amount of magma stored at depth before the onset of an eruptive event. Thus a first task in developing the genetic model of this section is to establish the volumes of magma that can be available for tapping even in present-day conditions, and to establish whether such volumes of magma have the potential to feed one event of LIP characteristics. If this task is successful, then we can consider that probably the difference between the LIP and the non-LIP event would be that the mechanism of extrusion in the former allowed tapping a larger volume of magma, whereas in the latter the tapped volume is smaller. The second task therefore would be to explore mechanisms that could explain such differences.

How Much Magma Can Be Stored under the Surface?

Based on seismic observation beneath zones of active volcanism, for example, underneath Italy or Japan, zones of low velocity likely to contain some melt can be defined as having lateral extensions of 200 km or even larger, and thicknesses in the order of 50–100 km (Nakajima et al., 2005; Panza et al., 2003). If we consider that melt proportions can be somewhere between 2% and 15% (e.g., Sato and Ryan, 1994) it can be concluded that typical volumes of present-day RPMs are of the order of 10^6 km^3. A similar volume would be found if, instead of considering the regional zones of seismic attenuation mentioned above, we focus on the zones of seismic attenuation beneath Hawaiian and Icelandic volcanoes, because the latter seem to have a diameter of ~130–175 km and equivalent thicknesses (e.g., Ryan, 1990; Watson and McKenzie, 1991). Even still larger dimensions of low-velocity zones could be obtained if attention was focused under other tectonically active regions (e.g., Grand, 1994). Although constraining the dimensions of an RPM and the amount of melt contained in it can be done within a certain degree of confidence from observation of seismic-wave propagation times for present-day volcanic provinces, this source of information should not be used to attempt a direct comparison with the volume of melt produced under any CFB during its formation because such comparison leads to the fallacy of four terms. Nevertheless, the danger of committing such a fallacy can be eliminated if magma volumes are estimated by using exactly the same method and identical premises in both CFBs and modern volcanic provinces alike. Consequently, at least from the point of view of logical reasoning, such comparison would be more acceptable than comparing magma volumes estimated by using different premises, even if the magma volumes estimated by our single method are not quite accurate.

As it turns out, it has been suggested that measurement of the content of rare earth elements (REE) in the volcanic products can be inverted to constrain the distribution of melt as a function of depth (White and McKenzie, 1995). Although the melt distributions obtained with this method are undoubtedly influenced by the choice of the mantle source and the form in which the melting process and transport mechanisms are envisaged, the key aspect of this method is that it can be used by assuming exactly the same premises to constrain melt distribution beneath any volcanic province, modern or past, and therefore the results of such inferences obtained from CFBs and modern volcanic provinces can be compared directly with each other without resulting in a fallacy associated with the existence of different premises. In other words, regardless of the limitations inherent in this particular method, the melt distributions obtained by using REE of the erupted products has the advantage of providing some information that can be used to make a quantitative comparison between modern and CFB provinces, thus avoiding any biases that could favor a particular genetic interpretation, even if only subtly.

Figure 4 shows a series of melt distributions as a function of depth obtained from various modern provinces that include mid-ocean-ridge (MOR) and intraplate settings (White and McKenzie, 1995). Although according to this method the magmas produced in MORs tend to be formed at shallower depths than the intraplate magmas (Fig. 4A), the same data also reveal that the

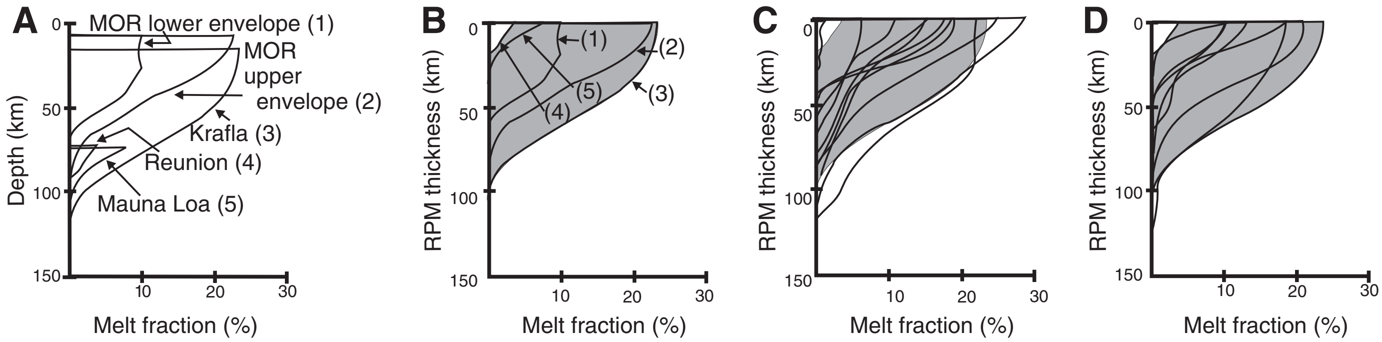

Figure 4. Melt distributions with depth inferred from rare earth element (REE) inversions made by White and McKenzie (1995). (A) Curves obtained from basalts from mid-ocean ridges (MORs) and intraplate volcanoes. For mid-ocean-ridge basalts (MORBs) only the upper and lower limits of the melt distributions are shown for clarity. The same curves of diagram A are shown in B, having their upper limit displaced, therefore emphasizing the dimensions of the various regions rather than the depths at which they are generated. The shadowed area is an envelope that is used for comparative purposes in C and D. (C) Comparison of the melt distributions of diagram B with those inferred from Siberian, Keweenawan, North Atlantic, Columbia River, Deccan, Etendeka, Paraná-Karoo, and Coppermine River basalts (representative examples from White and McKenzie, 1995). (D) Comparison of the melt distributions of diagram B with those inferred from various basalts and dikes ranging in age from 0 to 2700 m.y. RPM—region of partial melt.

inferred melt distributions define a layer of some 100 km regardless of tectonic setting (Fig. 4B). Such melt distribution curves imply that the average melt fractions (estimated as the areas to the left of the inferred melt distribution curves normalized by the thickness of the corresponding RPMs) are also relatively constant (~5%–15%) irrespective of the tectonic scenario.

In Figure 4C the depth-shifted melt distributions of several major CFBs, also obtained by using the REE method by White and McKenzie (1995), are compared with the depth-shifted distributions obtained from modern volcanic provinces. In this figure it can be observed that from the nearly 30 CFB-related melt distributions examined by White and McKenzie (1995) (only a representative selection was included in the figure for clarity), neither the associated thickness of the RPM nor the average melt content are extraordinarily larger than the upper limits of the present-day volcanically active provinces. Furthermore, it is found that even one of the CFBs, the Keweenawan Province, yields a melt distribution that is smaller than the lower limit of the modern volcanic provinces represented by the Reunion Volcano in these diagrams. Actually, the similarities between the melt distributions inferred to have existed under major CFB provinces can also be extended to include other minor basalt provinces, including lavas and dikes ranging in age from 0 to 2700 Ma, as shown in Figure 4D. In summary, the melt distributions inferred from REE of erupted products of both CFBs and modern volcanic provinces seem to have been produced in regions of partial melt with (1) a typical thickness of ~100 km, and (2) average melt contents between 5% and 15%. Such similarities further reinforce the possibility of having similar processes controlling volcano-magmatic activity in both types of provinces, rather than having extraordinary processes behind the formation of LIPs.

Although the REE method suggests that the percentage of melt might change drastically with depth, a conservative estimate of the typical melt content valid for all types of volcanic provinces can be considered to be 5% melt constituted uniformly in a layer 100 km thick. It is remarked that this approximation concerning the average melt content in a column of mantle rock is made only for the purposes of estimating representative volumes and does not provide an accurate representation of the rare element content of any particular eruption. Similarly, it is remarked that the diagrams of Figure 4 suggest that melt contents might exceed 20% locally (such large proportions of melt are restricted to layers ~40 km thick). Thus, a conservative estimate of the dimensions of a present-day RPM, and of its melt content, are used in the following calculations and are depicted in Figure 5.

A simple calculation based on the constraints shown in Figure 5 indicates that a regional zone of partial melting found beneath present-day active volcanic provinces conservatively might contain ~10^5 km^3 of melt. Using a different set of arguments, the presence of large volumes of melt trapped beneath the surface at a global scale was also noted by Schmeling (2000). Therefore, the argument of such melt storage is not entirely novel in the literature, although its significance in the genesis of LIPs has been overlooked until now. In particular, it has not been noted previously that the volume of melt trapped under certain regions of the Earth might be much larger than the volume of melt extruded in any single eruptive event either in a modern volcanic province or a CFB province. Actually, a typical eruption in a modern volcanic province extrudes a volume of magma of ~0.5 km^3, whereas that of a single extrusion event in the history of a CFB province might reach 600 km^3. It is observed that a typical present-day RPM conservatively can sustain >300 eruptive events of CFB proportions, and an incredibly larger number of eruptive events of modern volcanic province proportions. Remarkably, the number of eruptions that could be fed from the already existing magma in a present-day RPM would account for nearly 20% of the total volume of extrusive products characteristic of CFB provinces without requiring the production of a

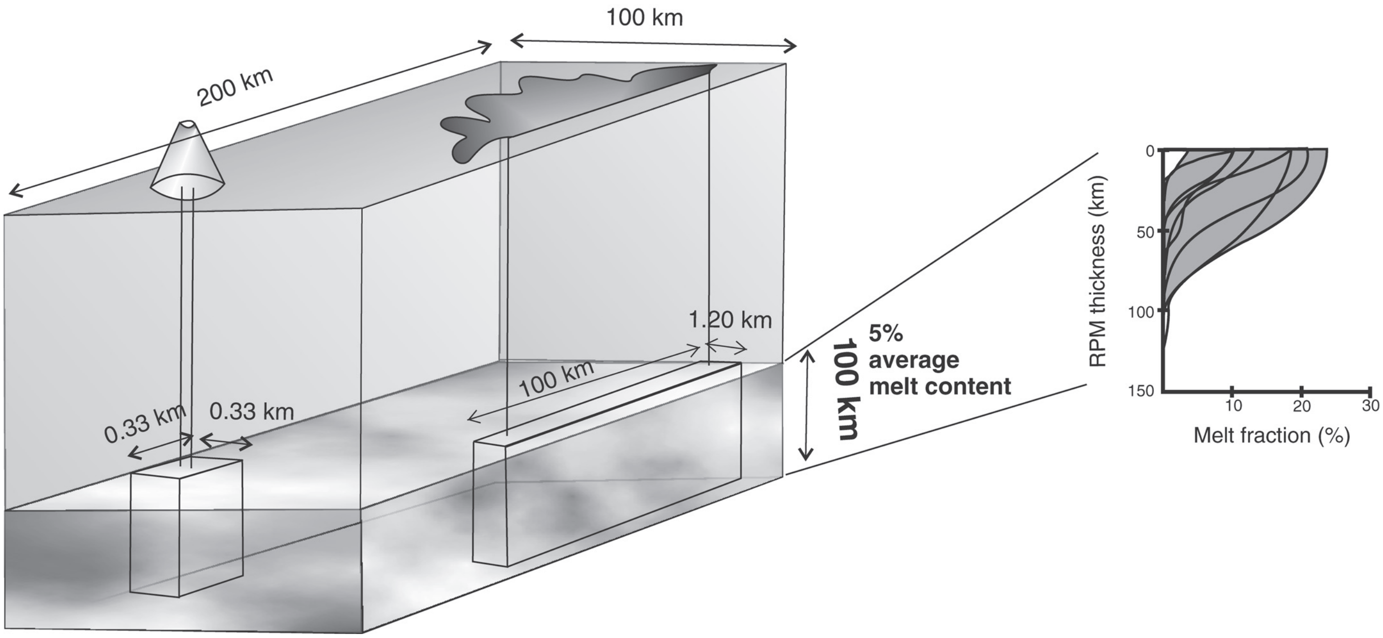

Figure 5. Schematic relation of the volumes of mantle rock required to produce the erupted volumes in one eruption of a normal volcano (cone) and a CFB-forming province (elongated feature on the surface). The average melt content of the melt zone is consistent with the constraints imposed by melt distributions inferred from rare earth element (REE) compositions of erupted products shown in Figure 4 and reproduced at the right of the diagram; the dimensions of the regional low velocity zone are shown in the upper part of the box. RPM—region of partial melt.

single additional drop of melt. Although this volume of melt is not enough to explain the formation of any CFB province, the percentage of volume obtained in this form is not at all negligible. Furthermore, if the calculations were made by using the limit of 15% melt (well within the limits allowed by observations), the volume of melt potentially existing at present beneath many RPMs would account for 60% of the volume of a typical LIP. Thus, it is clear that present-day volumes of magma trapped at depth have the potential to feed one event of LIP characteristics.

Mechanisms of Tapping Magma from the Deepest RPMs

If a typical present-day RPM has the potential to feed an eruptive event as volumetrically impressive as any event found in any CFB province, we need to explain (1) why is all of that melt not being extruded at present, and (2) what parameters could be responsible for the occurrence of such an efficient extraction process from time to time, so that a CFB province is formed. A clue to answer both of these questions can be found by focusing on key aspects that control the processes of melt extraction from its source and transport it to the surface as portrayed in the general model of volcanism advanced by Cañón-Tapia and Walker (2004). These authors argued that the conditions of melt interconnectivity within a region of partial melting (rather than the total amount of melt) and the overall state of stress of the rock overlying it are the two most important factors that control the style of volcanic activity at the surface. According to their model, a large degree of melt interconnectivity and a decrease in the magnitude of the compressive stress on the overlying rock promote a more efficient form of magma extraction than could take place if interconnectivity is small, or compressive stress is large. Therefore, their model predicts that an eruptive event capable of tapping large volumes of magma, like those forming CFB provinces, can take place only if an adequate combination of interconnectivity and stress is reached.

Establishing quantitative limits for the first of these two parameters (melt interconnectivity) depends on the knowledge of the dihedral angles relevant to all of the mineral phases that are likely to be found in a given parcel of mantle rock. As a first approximation, dihedral angles <60° yield a fully interconnected network of fluid-filled channels even for very small amounts of melt present in the system (Laporte and Provost, 2000b; von Bargen and Waff, 1986). Such an approximation, however, is valid only for monomineralic rocks with single valued solid-solid and solid-liquid interfacial energies. In natural systems some complications arise because these rocks are polymineralic, and in addition the solid-melt interfacial energies depend on the orientation of the interface relative to the crystalline lattice (Jurewicz and Jurewicz, 1986; Laporte and Provost, 2000a). Consequently, real magmatic systems might display a connectivity threshold even if the dihedral angles are in the range of 30°–60°, and perhaps more importantly, might display a strong 3-D dependence that will influence the interconnectivity of melt at a local scale (Holness, 2005). In particular, the degree of interfacial anisotropy is more pronounced for olivine, amphibole, and clinopyroxene than for quartz and plagioclase (Holness, 2005; Laporte and Provost, 2000b). Consequently, a marked influence of interconnectivity might be expected for mantle rocks, especially in those in which a preferred mineral orientation is suspected. Unfortunately, some discrepancies are found in the published dihedral angles of various mineral species (Holness, 2005), and therefore development of a truly quantitative model of a volcanic system that incorporates this parameter might be premature. Nevertheless, based on the current knowledge concerning the characteristics of the dihedral angle of the most relevant mineral species, some key premises seem to be justified. For instance, interconnectivity of the melt is unlikely to be uniform across the whole extension of an RPM. Variations are expected at various scales, depending on the distribution and orientation of the various mineral phases present in the original rock. Such variations in the interconnectivity of melt within an RPM are likely to influence the percolation process, and might prove to be an important factor that controls the total amount of melt that is capable of leaving an RPM upon onset of a tapping event. In particular, those regions of the mantle that had undergone the continuous influence of tectonic forces, and consequently that are likely to have developed a well-defined mineral fabric, are more likely to have an anisotropic interconnectivity than regions of the mantle exempt from those tectonic influences. For this reason, it is convenient to examine the consequences of such anisotropy.

Melt interconnectivity in a vertical direction contributes to the development of the conditions necessary for the initiation of a magma tapping event that allows the rapid raising of magma through a hydraulic fracture. The difference in density between the solid and liquid phases within the RPM produces a vertical force that promotes the ascent of the less dense phase (commonly the liquid) and the descent of the denser phase (usually the solid). Part of this process is better described as a two-phase flow taking place in a porous medium, where the viscosity of the liquid and the permeability (which in a sense is a measure of the interconnectivity of melt in the vertical direction) are important parameters (e.g., Fowler, 1990; McKenzie, 1985; Scott and Stevenson, 1986; Stevenson and Scott, 1991). Superimposed on the process of porous flow, the difference in density between solid and liquid promotes a different process that also contributes to the vertical migration of the liquid phase, and actually provides the only mechanism through which the melted rock is capable of reaching the surface without cooling back down to the solid state while traveling across a region of the mantle where melt is not thermodynamically favored. In simple terms, in addition to defining the vertical gradient of pressure controlling the porous flow (and compaction of the solid matrix), the lower density of the liquid phase within the RPM also is responsible for the onset of a vertical component of stress that is exerted upon the solid rock that forms the upper boundary of that region. The magnitude of that vertical stress is proportional to the difference in density between solid and liquid phases multiplied by the vertical dimensions of a column of liquid formed below the boundary of the RPM (Cañón-Tapia, 2009). In turn, such a vertical component of stress induces a horizontal component of stress within the solid rock directly on top of the liquid column, the magnitude of which is controlled by the elastic properties of the solid (in particular, its Poisson's ratio) and by the loading conditions. Owing to the large confining pressures commonly found on top of the deepest RPMs, the solid rock undergoing the vertical component of stress induced by the column of liquid underneath it would be unable to deform, and therefore the induced horizontal stress would be of a tensional nature with a much smaller magnitude than the vertical component inducing it (Turcotte and Schubert, 1982). Importantly, the total horizontal stress underwent by the solid rock at the boundary of the RPM is not necessarily tensional, because the induced tensional component is counterbalanced by the horizontal compression exerted by the adjacent rock. Nevertheless, the presence of a vertical column of liquid within the RPM induces a stress differential in the solid rock at its upper boundary, leading to a situation of metastable equilibrium (Cañón-Tapia, 2007). Such a metastable situation will be sustained as long as the vertical extension of the column of liquid does not reach a threshold value, determined by the combined effects of the confining pressure and the tensile strength of the overlying solid rock. When such a threshold value is reached, the solid boundary of the RPM starts to fracture, opening a space that will be filled in by the liquid in the column beneath it. This moment represents the initiation of a magma tapping event through the formation of a hydraulic fracture that eventually might lead to the emplacement of a dike or another tabular intrusion, depending on the orientation of the plane of the fracture relative to the vertical.

Although establishing the conditions of melt interconnectivity and internal stress required to initiate a magma tapping event is an important step toward a better understanding of the reasons for having volcanism akin to either CFB or modern volcanic provinces, we still need to examine the processes taking place after the initiation of such a tapping event in order to identify the most important parameters controlling the different styles of volcanic activity typical of both types of provinces. Following the general framework outlined by Cañón-Tapia and Walker (2004) we can identify three different processes starting to take place simultaneously after the onset of the fracturing event that initiates the tapping of magma. One of these processes concerns the movement of magma in the vicinity of the vertical column of magma that induced the first fracturing, and the other two concern the propagation of the fracture front away from the site of nucleation. The first of these processes is determined by the interconnectivity of melt in a horizontal direction, as such interconnectivity determines the effective permeability of the RPM, and in combination with the relevant viscosity and the resulting stress gradient determine how much melt can enter the forming fracture, and consequently the duration and size of the tapping event. The second of these processes is important, because the propagation of the fracture away from the RPM determines the fate of the moving magma either as an igneous intrusion stalled at a shallower level, or alternatively as an eruptive event that leads the magma from the RPM all the way to the surface of the planet. The third of these processes (the propagation of the fracture front away from the site of nucleation but remaining along the boundary of the RPM) exerts a strong influence in controlling the pressure conditions within the RPM, therefore determining the total volume of magma that can be extruded from the RPM in a given tapping event, and the dimensions of the igneous intrusion, which indirectly also determine whether a magma tapping event ends up as an eruptive event or not (Cañón-Tapia and Merle, 2006).

To illustrate the form in which all of the various parameters examined so far might lead to the formation of a CFB or to a volcanic province more akin to modern examples, it is convenient to present two examples that include some numerical calculations. The first step is to constrain the minimum amounts of magma required to initiate a magma tapping event. It can be shown that in general critical heights <100 km will suffice to initiate an event of hydraulic fracturing in most conditions of geological relevance (Cañón-Tapia, 2008, 2009). Actually, as shown in Figure 6, a column of liquid of 50 km should be able to induce an excess vertical component of stress exceeding 50 MPa almost independently of the depth at which the base of such a column of liquid is found. Owing to the fact that typical mantle material has a Poisson's ratio of ~0.25, according to linear elastic theory, such a vertical stress should induce a tensile horizontal stress >10 MPa in solid rock at the upper boundary of an RPM. Importantly, 10 MPa marks the typical tensile strength determined for most rock types

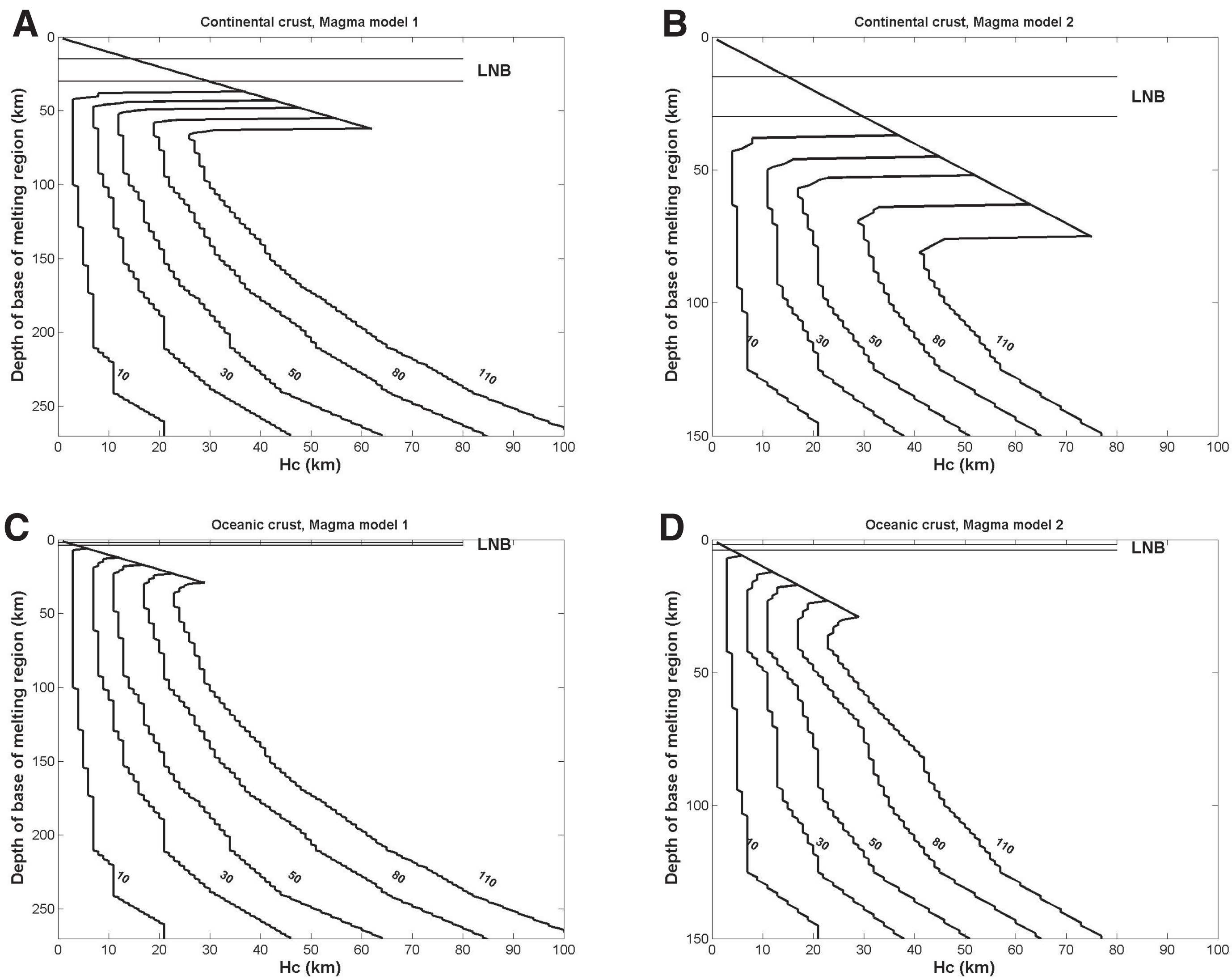

Figure 6. Diagrams showing the size of the critical heights of a column of magma required to exert a vertical stress of the amount shown numerically by each curve, as a function of the depth of the base of such a column. The two magma models correspond to densities of melt calculated from the two examples of Stolper et al. (1981), each applied considering a column of solid rock having either oceanic or continental crust above the melt (from Cañón-Tapia, 2009). LNB—level of neutral buoyancy; Hc—critical height.

(Jaeger and Cook, 1976; Turcotte and Schubert, 1982). Consequently, a minimum requirement for initiating a magma tapping event is to have uninterrupted continuity of the liquid phase in the vertical direction for at least 50 km below the upper boundary of any RPM. Importantly, this constraint in the vertical dimensions of the column of magma is independent of the total amount of magma present in the RPM. For example, 500 m^3 of magma would suffice to initiate a magma tapping event if all of this volume were contained in a narrow conduit having a horizontal surface area of 0.01 m^2 and a vertical extent of 50 km, but in contrast, even 10 km^3 of magma would not suffice to initiate a magma tapping event if this volume of magma were contained in a large pool with 1 km^2 of horizontal area and a depth of only 10 km. The difference between these two examples is that for the former the column of magma creates a sufficient vertical stress to induce a horizontal tensional stress slightly larger than tensile strengths of most rock, whereas a larger pool of magma only results in a vertical excess stress of <10 MPa in most areas of geological interest, which would induce a tensional horizontal stress <3MPa in most cases, being less than the typical tensile strength of most rocks. Consequently, whereas the minimum volume of magma required to initiate a magma tapping event can be constrained using hydrostatic principles, there are no constraints that can be imposed on the maximum volumes involved in any tapping event other than perhaps specifying a maximum melt fraction for a given volume of mantle rock. Nevertheless, the exact distribution of this liquid within the RPM, controlled to some extent by the degree of horizontal interconnectivity, plays an important role in controlling the outcome of any tapping event, as discussed next.

A detailed description of possible outcomes of magma tapping events is outside the scope of the present chapter, but a general examination of two extreme situations should serve to illustrate the two extreme behaviors likely to result from an eruptive event akin to either a CFB or a modern volcanic province. For the two situations to be considered here, I assume that an RPM has lateral dimensions of 100 km × 100 km, a thickness of 50 km, and contains an average 1% melt (Fig. 5). As discussed above, these dimensions are well within the range deduced from both seismic signals and the REE content of the erupted products. From the total 500 km^3 of melt contained in the RPMs of each of the two examples, I focus attention on only 120 km^3 of liquid for simplicity. The same calculations can be done by using any other prescribed volume considered representative of the volume of individual eruptive events in CFBs without altering the result.

In one case, I consider an RPM having 120 km^3 of melt concentrated in two zones, each having 20 km × 1.2 km in the horizontal direction and 50 km in the vertical direction. The other example RPM has the same 120 km^3 of magma dispersed in 445 parcels of rock, each having horizontal dimensions of 0.33 × 0.33 km and with a vertical extension of 50 km. In both RPMs the remaining 380 km^3 of magma is considered to be uniformly distributed in the remaining 47,600 km^3 of mantle rock that defines the RPM. In other words, although the average melt content of each of the example RPMs is equal to 1%, the melt is concentrated in regions having 5% melt concentration and in regions having 0.8% melt, and those regions of higher melt concentration are distributed differently in each case.

Considering that the liquid is assumed to be distributed in volumes of mantle having the same vertical extension in both scenarios, the probability of having an uninterrupted column of magma capable of initiating a tapping event will be slightly higher in the volumes of mantle with higher melt concentrations, and therefore I focus on these zones. Where the zones of melt concentration are small, the volume of magma likely to be tapped by any propagating fracture will be restricted to the melt contained by the region directly surrounding the first fracture. This volume of melt is on the order of 0.27 km^3, corresponding to the volume of magma erupted in a volcanic eruption of a modern volcanic province. Actually, even if the fracture extended beyond the horizontal limits of one region of high melt concentration, the lateral extent of this fracture would add only very small volumes of melt to the tapping event because it would be piercing the surface of a volume of mantle with very small amounts of magma. Because the mechanism driving the propagation of the fracture front both in the horizontal and vertical dimensions depends on the volume of melt that is entering the newly formed crack (Cañón-Tapia and Merle, 2006), it is unlikely that one single fracture could propagate long enough along the surface of the RPM to intersect a second region of high melt concentration. Consequently, any tapping event taking place in this RPM is likely to involve very small volumes of magma at a time.

For the RPM having only two zones of relatively high melt concentration, any fracture that starts tapping magma is likely to involve up to 60 km^3 of liquid in one single event. The tapping of such a volume of magma could take place through a conduit of relatively limited horizontal extension, provided that the horizontal interconnectivity is sustained at all times within the zone of melt concentration, or alternatively it might involve a fracture with a horizontal extension of a few kilometers in one direction if the fracture allowing the mobilization of magma grows along the top of the RPM parallel to the longest horizontal extension of the zone of melt concentration. In either case, a volume of liquid corresponding to one volcanic eruption of a CFB province will have been tapped in one single event with relative ease.

Despite the fact that both examples shown in Figure 5 are highly artificial, they serve to illustrate the type of processes that might take place during a real tapping event as well as the roles of the various parameters involved. At a minimum, the examples provided here illustrate the fact that, at least in theory, two contrastingly different eruptive behaviors can originate from RPMs that contain identical melt fractions and total amounts of magma. Variations of the internal distribution of such melt, rather than of actual melt content, might suffice to explain the different eruptive behaviors typical of CFBs and modern volcanic provinces. In addition, these examples suggest that such variations in the internal concentration of melt within a given RPM can also explain why a present-day RPM might not be feeding a CFB, giving some clues concerning the processes that could lead to the achievement of the conditions required for the creation of such a province from time to time.

Geological Context

According to the previous findings, in order to explain with more detail we need to focus attention in the processes that could lead (1) to the uneven accumulation of melt within an RPM, and (2) to favor the rupture of the upper boundary of the RPM for long distances. One possible alternative to satisfy both conditions certainly is related to the action of mantle plumes. These explanations, however, are not unique. A very reasonable scenario that could lead to the same result can be derived from the observed coincidence between CFBs and zones of lithospheric discontinuity, such as craton boundaries or ancient shear zones (Anderson, 1994). King and Anderson (1995) showed that a marked difference in lithospheric thickness can induce a small-scale mantle convection capable of producing an RPM with zones of melt concentration exceeding 2%. According to their results, the more marked the difference in lithospheric thickness, the more extensive the zones of melt accumulation, and consequently the larger the volume of melt that could be stored within the RPM. Furthermore, their model results show that the regional zone of partial melt would not have a homogeneous distribution of melt, but rather that melt will tend to be concentrated in two or three broad zones (depending on the actual difference in lithospheric thickness), separated by zones with a lower concentration of melt. Although those results evidently represent a highly idealized situation, the general feature of an extensive regional zone of partial melt with zones of melt concentration separated by zones of lower melt concentration is precisely one of the conditions required by the model developed in the previous section.

Actually, the same mantle geometry explored by King and Anderson (1995) has characteristics that favor the rupture of the RPM for long distances. Analogue models of overpressured magma chambers with different geometries (Cañón-Tapia and Merle, 2006) have shown very clearly that rupture events are more likely to nucleate in those places on the surface of the chamber with a larger angularity and that such angularities guide the propagation of the fracture along the surface of the chamber once it had started to form. For this reason it seems reasonable to consider that the angularities associated with the step geometry resulting from a marked difference in lithospheric thickness could serve as nucleation sites for the occurrence of fractures that allowed the rapid tapping of the magma formed as the result of the small convection cells. Finally, it is also noted that the vertical dimensions of the zones of higher melt concentration in the numerical results of King and Anderson (1995), are well within the limits of the 100 km required to initiate a tapping event based solely on the difference in density of the magma with its surroundings, as shown above. Consequently, unlike the conclusions reached by King and Anderson (1995), it is considered here that a mechanism for the melt to reach the surface does indeed exist, even without having an external source of lithospheric extension. In any case, if such an extension occurred as the result of other larger scale processes, the initiation of the fracturing event will be facilitated, and actually could be achieved by columns of magma of <50 km height.

In summary, the model presented in this section envisages CFBs and modern volcanic provinces as the result of the same basic processes. The most striking difference between both provinces—the large difference in the typical volumes of the erupted products—can be explained as the result of some special conditions, which nonetheless have nothing extraordinary or anomalous. For this reason, it is concluded here that CFB provinces, and by extension, LIPs, are not necessarily the manifestations of a significantly different mode of operation of the Earth but rather one extreme of a spectrum of possible outcomes that can take place during the combination of the various parameters involved in controlling volcanic activity. Relatively small variations in some of these parameters are likely to have been responsible for the wide diversity of features displayed by LIPs and modern volcanic provinces alike, including those related to chemical composition.

DISCUSSION

Until now the debate concerning the origin of LIPs has centered on the mechanisms required to produce large amounts of magma in a relatively short time interval. For the various reasons discussed in the first sections of this chapter, this feature of LIPs is prone to lead to fallacious judgments, and consequently it promotes mythical thinking. Perhaps the most notable exceptions to this trend have been the works by Silver et al. (2006), who envisaged CFBs as "drainage events" rather than "melting events," and that by Jerram and Widdowson (2005), who focused more on the internal facies architecture and structure of CFBs, pointing out that these provinces are not as uniform as commonly portrayed.

In a way, this work has the same general conceptual framework that is found behind those two works because more attention is given to the extrusive expression of those provinces, and such expression is explained more in terms of a mechanism that allows a more efficient drainage of magma, avoiding any dependence on magma production rates. Nevertheless, important differences exist between the model proposed by Silver et al. (2006) and the model advanced here, which deserve further examination. First, it is noted that the model developed here is a particular example of the model of volcanism developed by Cañón-Tapia and Walker (2004), which is of a more general nature because it concerns all expressions of volcanism and is not constrained exclusively to explain the occurrence of cratonic flood basalts. Second, the model developed here does not make a distinction between the stage of formation and maintenance of a reservoir of magma, and the stage of drainage. Unlike the model developed by Silver et al. (2006), in the model developed here the region of partial melt is considered to be the natural expression of the tectonic evolution of the Earth because it simply marks the region where the pressure-temperature conditions of any parcel of mantle are such that they can sustain the melting of some of its constituent minerals. These conditions seem to be globally met below an average depth of 100 km under continents, coinciding in extent with the globally detected seismic discontinuity (Thybo and Perchuc, 1997), and therefore are not exclusive of the cratonic environments. Actually, the presence of those regions is responsible for the occurrence of volcanic activity around the world, whether related or not to a LIP. Third, Silver et al. (2006) divide the drainage stage in two separate and sequential substages. In the first of these substages, porous-flow migration of magma is envisaged to collect at depth, and in the second substage the collected magma ascends, forming dikes in the process. Such a distinction between the collection and drainage substages is not present in the model presented here because the initiation of a dike does not rely on the previous collection of magma in a pool on top of the RPM. Actually, in my model the porous flow of magma within an RPM can be envisaged as being responsible for the uneven lateral transport of the melt within the zone of partial melting, therefore defining the dimensions of the zone of influence of a tapping event, which explains the observed differences in the volumes of erupted products in the various provinces around the world. Consequently, unlike the model of Silver et al. (2006), the model developed above explicitly accounts for the episodic character of the many events that form a CFB province. As pointed out by Jerram and Widdowson (2005), such an episodic character is commonly neglected in calculating average rates of formation of CFB provinces, but it is marked by the fact that not all of the magma was extruded during one single eruptive event. Also, the model developed here can explain in simple terms the occurrence of an extended period (i.e., beyond the 1 m.y. limits) of volcanic activity at or very close to the areas of formation of CFBs, the occurrence of which is sometimes neglected in the interpretation of these provinces, as pointed out by Sheth (1999a).

Incidentally, the model developed here not only accommodates the occurrence of an extended period of volcanism beyond the peak of activity in forming a CFB, but it also serves to explain the occurrence of portrayed volcanism in other types of tectonic settings. For example, the same basic principles have been used to explain the occurrence of volcanism a long time after subduction had ended along the Peninsula of Baja California (Negrete-Aranda and Cañón-Tapia, 2008), and this might serve to explain the intermittent occurrence of volcanism in places like the Tibetan Plateau. In all of these instances the protracted period of volcanic activity represents the "normal" magmatic activity of the region being disrupted by a transient effect acting as stress concentrator. For the CFB, events such as a global plate reorganization might provide the required external disruption, but a more localized disruption might suffice to trigger a bout of volcanic activity. Such a renewed (or enhanced) bout of volcanism comes to an end once the effects of such a transient event on the Earth's surface wanes. In this context, it is also noted that the observations suggesting that deformation style, and hence stress distribution, varies progressively along the rift axis during rift propagation (van Wijk and Blackman, 2005). This should explain why CFBs, or LIPs, do not form an uninterrupted chain along places of continental breakout. Either the places where no volcanic activity of this type occurred were characterized by a smoother difference in lithospheric thickness across the rift, or the local stress distribution was not enough to allow the tapping of magma all the way to the surface. In particular, the latter alternative is an aspect of the model developed here that might need some clarification.

In the model developed above, emphasis was placed on the conditions favoring the initiation of a diking event, allowing the rapid tapping of magma out of its region of origin or storage. Although some mention was made about the role played by the propagating front of such a fracture away from the RPM, so far no constraints concerning the final end of the tapped magma had been imposed, and somehow it could have been that the model made the implicit assumption that the tapped magma was directly erupted at the surface. Actually, the conditions examined in the previous section only concern the initiation of a fracturing event for the deepest RPM that was justified from all available evidence (seismic, geochemical, petrological, etc.). Nevertheless, those conditions do not suffice to justify an assertion in the sense that the magma tapped from those depths is erupted at the surface as a result of a single tapping event. Actually, using the same hydrostatic arguments that were used to constrain the critical heights of magma required to initiate a fracturing event shown in Figure 6, Cañón-Tapia (2009) also assessed the probability of a single tapping event originating at the deepest RPM to reach the surface. In particular it was noted that the vertical end of a propagating fracture needs to pierce rock of different mechanical properties upon its ascent. The mechanical state of those rocks depends on the lithology, the tectonic setting, and even their prior history, and consequently, a wide range of situations is likely to have taken place in nature. Without attempting to be exhaustive, however, some constraints can be derived from general situations such as those shown in Figure 7. As shown in the Figure 7 diagrams, the vast majority of propagating fluid-filled fractures will be unable to pierce the upper layers of rock under most conditions. This situation can lead to two possible alternatives. One alternative is that the magma coming from below simply stalls at the rheological boundary, forming a sill or other large pluton, and so the magma never reaches the surface. The other alternative is that the stalled magma eventually finds its way to the surface owing to a change in the mechanical condition of the rock above it. The first alternative evidently would explain the occurrence of very large intrusive complexes, such as the Bushveld (Cawthorne and Walraven, 1998) or the Skaergaard intrusion (Tegner et al., 1998). The second alternative would explain some of the geochemical and petrological signatures of most LIPs that suggest some residence time of magmas at relatively shallow levels, and depending on the heterogeneity of the source region it could also explain some of the geochemical trends observed in some LIPs (e.g., Smith, 1992). Which of these alternatives takes place in every case, might depend on a combination of several factors, among which might be the mechanical weakening of the overlying crust owing to the repeated input of magma from below (Annen and

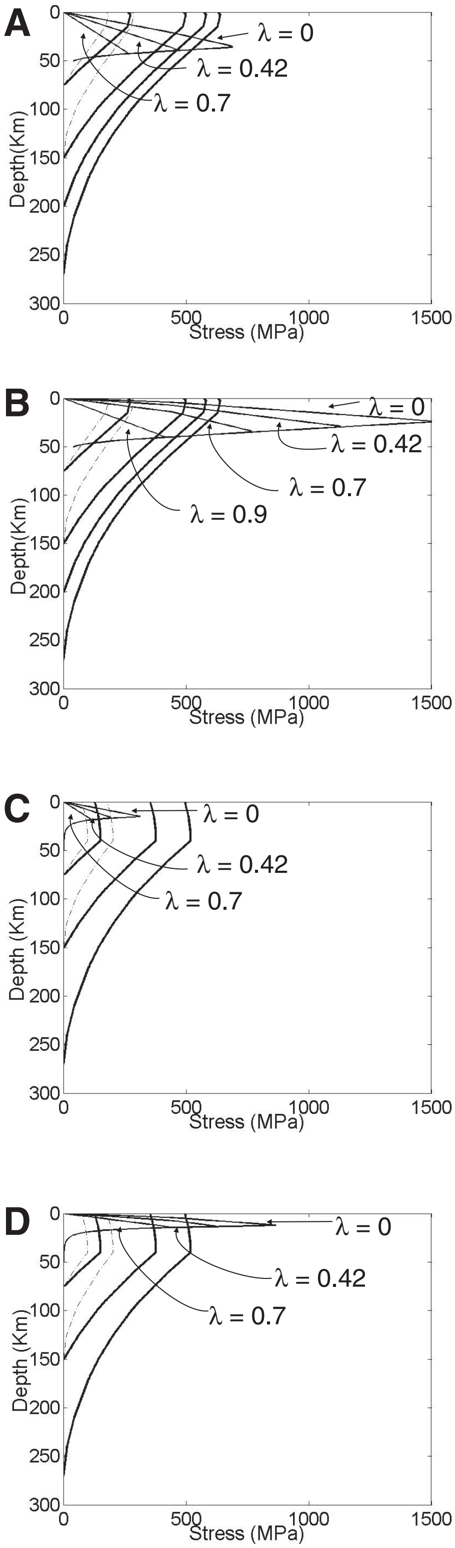

Figure 7. Diagrams showing the relationship between the hydraulic head of an ascending column of magma and the strength of the solid rock as a function of depth (from Cañón-Tapia, 2009). Only the magma columns to the right of the rock-strength curves are able to rise all the way to the surface, with the rest remaining trapped at depth by a rheological boundary.

Sparks, 2002), or a reduction of the horizontal stresses from external, larger scale processes. Consequently, only a detailed analysis of the evidence on a case by case basis could provide the required elements for answering such a question. Such a level of interpretation is beyond the scope of the present work, although the lack of specific examples does not invalidate the general constraints outlined here.

Finally, it is noted that much of the discussion so far has assumed that magma production is completely halted within the RPM of reference, and we had focused only on the processes of tapping such magma. If we remove such constraint, by acknowledging that mantle rocks are likely to undergo some movement when time scales of the order of 1Ma are considered, and that such movement might contribute to the creation of an additional amount of melt in some cases, it turns out that the volume of magma that can be extruded from a region of partial melt analogous to those active today in a 1 m.y. interval can be increased substantially. For instance, consider that the eruption rate for Hawaiian volcanoes has been calculated to be somewhere between 0.03 and 0.1 km^3/yr (Lipman, 1995; Vogt, 1979). Following Figure 5, this magma can be assumed to represent the volume of magma produced by the prism of mantle rock directly beneath each of the active volcanoes in Hawaii. Taking into consideration the surface area of these volcanoes (from 6 to 10 × 10^3 km^2 including the submarine portion), it can be concluded that the region of partial melt depicted in Figure 5 could produce 2 to 4 times as much magma as underneath a single Hawaiian volcano in the same period of time (i.e., from 0.06 to 0.4 km^3/yr). Therefore, in 1 m.y. the amount of magma would extend from 6 × 10^4 to 4 × 10^5 km^3, which would add an additional 40% of the volume of a CFB.

In summary, by comparing the melt distributions as a function of depth inferred from the composition of erupted products, and combining this information with the dimensions of present-day regions of partial melt under zones of active volcanism, it is found that at present an RPM has the potential to produce a similar volume of extruded products in a CFB province in a time interval of 1 m.y. Consequently, this model shows that the difference between CFBs and modern volcanic provinces might not be the rapid production of melt under the surface, but probably it might be related to a more efficient form for extracting that melt from its region of origin. The basics of such a mechanism were outlined in the previous section.

CONCLUDING REMARKS

Undoubtedly, more detailed studies need to be undertaken to provide a more robust model than the one developed here to fully explain the origin of LIPs. In particular, geochemical and petrological aspects of the erupted products need to be examined with more detail in the light of this model. Nevertheless, the approach followed here avoids as much as possible many of the fallacies that have been commonly made when addressing the origin of LIPs, highlighting the fact that there is no need to invoke an extraordinary or abnormal mechanism to explain the occurrence of such volcanic provinces.

In the strictest sense, the model developed here does not invalidate models explaining the origin of LIPs in terms of the occurrence of mantle plumes, but it is also true that such models are not so robust as to exclude any other non-plume explanation without further inquiry. Consequently, it is only fair to say that the mantle-plume origin of LIPs remains a good working hypothesis rather than being a well-established fact beyond any possible objection. Thus, plume and non-plume hypotheses deserve equal treatment, which is only possible if mythical thinking is avoided.

As pointed out by Dickinson (2003), avoiding mythical thinking is important to foster a better understanding of a particular phenomenon for several reasons. First, it helps us to acknowledge uncertainty forthrightly, which is a necessary step in the search for real solutions. Second, by allowing ourselves to entertain alternative explanations, even if some of these might be based on relatively inconclusive evidence at the beginning, we might be able to identify clues that could have been ignored otherwise. Third, by entertaining alternative explanations we do not imply that the dominant explanation is straightforwardly incorrect. Fourth, the strengths of the dominant approach might be better appreciated once the real weaknesses of the alternative models have been objectively established. Consequently, to avoid mythical thinking it is necessary to examine alternative hypotheses, each of which should allow us to delineate a series of critical observations that can be used in future studies to test its validity. However, it is also equally important to consider that some of the critical observations required to test an alternative model might not be available at a given time, not because it is technologically impossible to make them but because the dominant model did not require them. Under such circumstances, it would be unfair to reject the alternative hypothesis only because it has not been explored as deeply as the dominant model, which would therefore reinforce the selective bias in favor of the predominant model typical of mythical thinking. Consequently, to avoid as much as possible such biasing we need to be careful not to ask for more conclusive evidence from an alternative hypothesis than we asked from the dominant model when it was in its initial stages, and furthermore we should accept the challenge of making the necessary observations that can help us to decide in the future whether this alternative approach is reasonably valid or not. The model developed here is a step in that direction, and hopefully the discussion made here concerning the form in which premises might influence our thinking concerning a given subject will be helpful in focusing on the role played by various premises behind the various alternative models proposed mainly in the past 10 yr in explaining the origin of LIPs by a mechanism other than mantle plumes.

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