

## Distribution of agromineral resources in space and time – a global geological perspective

**Abstract** – Agromineral resources are minerals and rocks used to improve soil productivity and health. These resources can be applied: indirectly, by extracting and concentrating one or more minerals by industrial processes for the production of conventional, highly soluble fertilizers; and directly, without processing, except fine grinding, for direct soil application. Agromineral resources include sedimentary phosphates, limestones/dolostones, potash and glauconite-bearing rocks of sedimentary origin, basaltic rocks, phonolites, kamafugites, and glass-rich mafic rocks of igneous origin. Among metamorphic agromineral resources, marble and biotite schist stand out. However, agromineral resources are not equally distributed on Earth's surface, occurring more in one area than in another, and have accumulated in various geotectonic settings related to plate tectonics, being formed in specific geological time periods in Earth's history. Therefore, these resources occur in specific “agromineral provinces” and were formed during specific “agromineral epochs”. This paper provides a conceptual framework for agromineral resource distribution in time and space. Agrominerals have a high potential to be used as directly applied soil amendments and soil remineralizers for new and innovative farming strategies, provided the amendments are low or free of contaminants.

**Index terms:** mineral resources, agrominerals, fertilizers, soil amendments, soil remineralization.

## Distribuição de recursos agrominerais no tempo e no espaço – uma perspectiva geológica global

**Resumo** – Recursos agrominerais são minerais e rochas usados para melhorar a produtividade e a saúde dos solos. Esses recursos podem ser aplicados: indiretamente, ao se extrair e concentrar um ou mais minerais por meio de processos industriais, para produção de fertilizantes convencionais e altamente solúveis; e diretamente, sem processamento, exceto moagem em tamanho fino, para aplicação direta no solo. Recursos agrominerais incluem fosfatos sedimentares, calcário/dolomito, potassa e rochas portadoras de glauconita de origem sedimentar, basalto, fonólitos, kamafugitos e rochas máficas ricas em cristais e de origem ígnea. Entre os recursos agrominerais metamórficos, destacam-se o mármore e o biotita xisto. Contudo, os recursos agrominerais não são distribuídos homogeneamente pela superfície terrestre, ocorrendo mais em uma do que em outra área, e têm se acumulado em diversos ambientes tectônicos relacionados às placas tectônicas, tendo sido formados em períodos geológicos específicos na história da Terra. Portanto, esses recursos ocorrem em “províncias agrominerais” específicas e foram formados durante “épocas agrominerais” específicas. Este trabalho apresenta um framework conceitual referente à distribuição dos recursos agrominerais no tempo e no espaço. Os agrominerais têm potencial para serem usados como amenizantes aplicados diretamente ao solo e como remineralizadores de solo, para estratégias novas e inovadoras de agricultura, desde que os amenizantes sejam poucos ou livre de contaminantes.

**Termos para indexação:** recursos minerais, agrominerais, fertilizantes, amenizantes de solo, remineralização do solo.

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## 1. Introduction

The population on Earth is facing unprecedented challenges with regards to food and water. The basis for healthy and sustainable farming systems is to feed soil and plants with sufficient nutrients and water, and to manage the soil in a way that is sustainable and less destructive to the environment. The geological basis to feed soils, plants, and people consists of naturally occurring rocks and minerals that can supply nutrients and improve soil physical conditions (Theodoro & Leonardos, 2006; van Straaten, 2006). Agromineral resources, applied together with organic matter, can be used to simulate the soil systems that occur naturally and to develop and sustain healthy agroecosystems.

In a global context, agromineral resources cover a multitude of mineral materials that are applied in agriculture, horticulture, fruticulture, and forestry (van Straaten, 2007), being used:

1. for the extraction of one or more minerals by industrial processes, principally for the production of conventional, highly soluble fertilizers, such as phosphate rocks and potash;
2. without major processing, for direct application in agriculture, including some phosphate rocks and high phosphate-silicate rocks, as, for example, “verdete” and phonolites in Brazil;
3. to improve the physical properties of soils, mainly pumice, perlite, vermiculite, and zeolites, most of which are applied in the horticultural industry;
4. primarily to enhance the pH of soils, e.g., liming materials as limestones and dolostones;
5. as a main or coproduct to reduce aluminum toxicities, such as gypsum;
6. as multi-nutrient coproducts for other applications, including basalt fines from aggregate production and nepheline-syenite fines from nepheline extraction for the glass industry in Norway;
7. as single-nutrient coproducts for other applications, e.g., K-rich biotites concentrated from fines of granite processing;
8. as a concentrate from coproducts of the aggregate industry;
9. as coproducts from waste created by the extraction of precious and semiprecious minerals, e.g., kimberlite diamond operations,

phlogopite from the emerald industry, or basalt from amethyst extraction industries in Brazil;

10. as agrominerals from finely ground “rejects” in large tailing ponds at extractive industries, such as phosphate industries;
11. as special agrominerals, to reduce ammonia losses from animal manures and composts, e.g., zeolites, or as feed additives for animals; and
12. as agrominerals obtained from mine wastes, especially industrial mineral mines.

In the case of agromineral resources that include raw materials for conventional fertilizer production, the geologist looks for naturally occurring resources with a high grade of natural concentration and a high potential for economic industrial processing. In the case of agromineral resources that include rocks for direct application without industrial concentration and processing, except fine grinding, the geologist looks for local geological materials that may be coproducts of other industries or resources developed primarily to serve local agricultural development. The applications of these agromineral resources are intended to restore ecological balances and rejuvenate and remineralize soils.

This paper will provide a geological perspective of agrominerals in a global context, focusing on the geological aspects of Earth’s agromineral resources. It aims to: discuss the geology of the main types of agromineral resources that can be used to enhance soil productivity and increase food quantity and quality, provide some geological context and definition of agromineral provinces and epochs, and present the global distribution of agromineral resources in space and time in a plate tectonic model, followed by a short review of the main agrominerals as sources of nutrients and as substrates to improve soil physical properties.

## 2. Agromineral resources

Agromineral resources are minerals and rocks that enhance soil productivity both chemically, by providing nutrient sources to soils and plants, and physically, by improving soil physical properties, such as water holding capacity, water availability, aeration, and structural support (van Straaten, 2007). For the production of fertilizers, the most used resources include nitrates, phosphate rocks, potassium-bearing salts like potash (KCl), and K sulfates (van

Straaten, 2007). For direct application and general soil improvement, the used agrominerals comprise igneous rocks such as basalt and phonolite/nepheline syenite, as well as ultrapotassic volcanic rocks and/or rocks of sedimentary and metamorphic origins as biotite mica schists (van Straaten, 2007). Among the latter resources, stand out those used to: provide plant nutrients; increase the pH of acid soils, as, for example, liming materials from carbonate sediments; reduce Al toxicities, mainly gypsum and finely ground basalt; increase cation exchange capacities in soils and other growth media, particularly vermiculite, zeolite, and finely ground basalt; increase aeration in soils, mostly perlite and pumice; and enhance soil moisture retention. Agromineral resources also include rocks that contain the secondary nutrients calcium, magnesium, and sulfur, especially limestones/dolostones and gypsum, besides K-rich sediments like glauconite/illite-rich rocks (van Straaten, 2007). In Brazil, extensive glauconite/illite-rich resources have been identified as “verdete” (Guimaraes et al., 2000; Santos et al., 2015).

However, while many researches have been conducted to define and outline the so-called “metallogenic provinces” and “metallogenic epochs” (Lindgren, 1909; Petraschek, 1965; Kesler, 1978; Guilbert & Park, 1986), only a few studies have been carried out on nonmetallic materials, specifically agromineral resources. Some examples are the works of: van Straaten (1987), who described the geological settings and geological events in which a specific agromineral or group of agrominerals occur in East Africa; and Mathers (1992, 1994), who provided information on the potential of nonmetallic minerals and “industrial minerals” in parts of Central America and Uganda, respectively, whose geology was grouped into “terranes” or “domains” – in each domain, the author also described characteristic and predictable suites of industrial minerals, including agromineral resources.

It has been known for many decades that some agromineral resources are spatially related to certain sedimentary environments and processes (Cook & McElhinny, 1979; Notholt, 1980a; Sheldon, 1980), as well as to igneous events and associations, such as, for example, carbonatites in specific structural positions. The abundance of specific agromineral resources, as phosphate rock or K-bearing evaporites, differs in a geological time frame, with some time periods in Earth’s history being more conducive to agromineral resource

concentration than others (Cook & McElhinny, 1979; Ronov et al., 1980; Hardie, 1996; Warren, 1999, 2006). The distribution of highly concentrated sedimentary agrominerals in a specific period reflects times of nutrient resource concentration related to exogenic environmental changes associated with climate, plate positions, terrestrial input rates, and current oceanic configurations.

Agromineral resources occur primarily but not exclusively in sedimentary and igneous environments. A few resources, such as marble and biotite mica schists, are found in metamorphic terranes, while others, including nitrates, sedimentary phosphates (phosphorites), K salts, and sulfates (such as gypsum, carbonates, and K-rich sediments, e.g., glauconite-bearing sandstones), are observed in sedimentary environments (Guimaraes et al., 2000; van Straaten 2007; Santos et al., 2015). Some agromineral resources – elemental sulfur, perlite, and pumice – are related to igneous activities, mainly volcanism, whereas others are related to carbonatites and alkaline complexes, phosphate rocks, vermiculite, and carbonates; K-rich volcanic rocks are found in specific geological environments (van Straaten, 2007).

In igneous environments, agrominerals occur as igneous phosphates, igneous carbonates, and vermiculite, associated with carbonatites and other much rarer igneous rocks such as kamafugites (Brod et al., 2000; van Straaten, 2007; Simandl & Paradis 2018). As part of worldwide and regional compilations, Deans (1966), Notholt (1979, 1980b), Heinrich (1980), Woolley (1987, 2001), Notholt et al. (1990), Kogarko et al. (1995), and Simandl & Paradis (2018) described minerals related to carbonatite complexes.

The uneven distribution of sediments in time and space in the context of large-scale geochemical cycling has been extensively investigated by, for example, Garrels & Mackenzie (1971), Ronov et al. (1980), Berner et al. (1983), Hay et al. (1988), Hay & Wold (1990), and Hardie (1996). These compilations include studies on: the global distribution of sedimentary agrominerals, such as sedimentary phosphate rocks (Cook & McElhinny, 1979; Notholt, 1980a, Pufahl & Groat, 2017), the secular variation of seawater and precipitation of K salts (Hardie, 1996), and carbonates in general (Ronov et al., 1980; Berner et al., 1983). Several works have also shed some light on possible cause-effect relationships, trying to find

some explanations for the uneven temporal and spatial distribution of sediments (Cook & McElhinny, 1979; Ronov et al., 1980; Warren 2006).

### 3. Agromineral provinces and agromineral epochs

Similarly to metallogenic provinces, agromineral provinces are defined as areas characterized by a particular assemblage of agromineral deposits or by one or more characteristic type of agromineral resource accumulation in a well-defined geographical area (Cook & McElhinny, 1979; van Straaten, 2007). The province may have had one or more episodes of an abnormal concentration of agromineral resources. Examples are the “Moroccan sedimentary phosphate province” and the “Kola igneous phosphate province”, where igneous phosphates are found and mined in the Kola Peninsula of Finland and Russia.

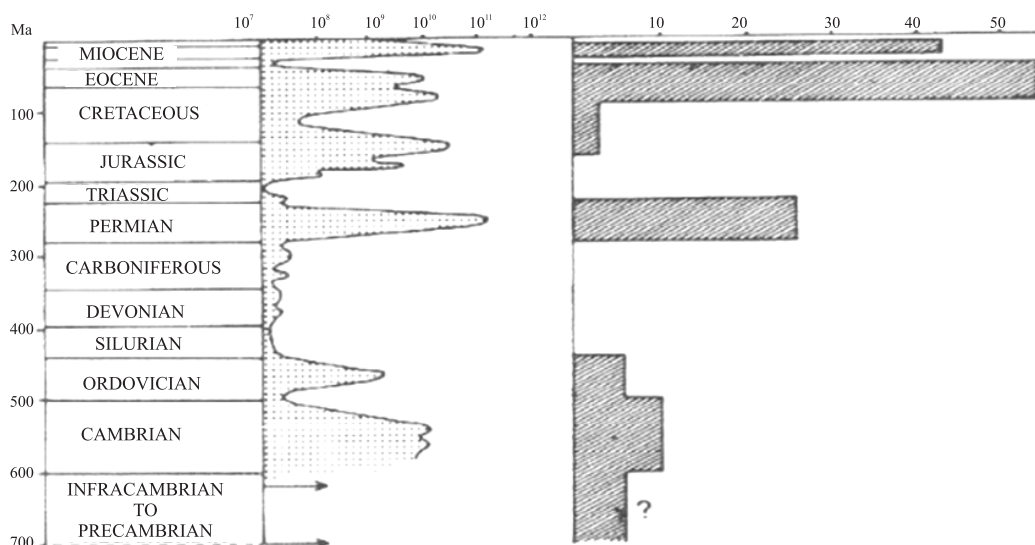
Agromineral epochs are defined as geological time spans favorable for the accumulation of agromineral resources (van Straaten, 2007). An example is the “Neoproterozoic/Cambrian sedimentary phosphate epoch”.

### 4. Agromineral resources in space and time

In this section, the geological framework and distribution of agromineral resources in space and

time will be discussed. The generalized spatial distribution of these resources is viewed in the context of plate tectonic settings, associated with the geological evolution of oceans and continents and the changing environmental conditions in oceans and on land.

Phosphorus is found in mineral deposits in two principal forms: as phosphate-rich sediments, called phosphorites (>15%  $P_2O_5$ ); and as igneous phosphates primarily related to carbonatites (Cook & McElhinny, 1979; Notholt, 1980a; Sheldon, 1980; van Straaten 2007). The temporal distribution of phosphorites has varied strongly over the past 570 million years (Cook & McElhinny, 1979; Sheldon, 1980), as shown in Figure 1. The distribution of the main phosphorite deposits over time is largely a reflection of periods in which major global biogeochemical and climatic changes took place. One of the main contributing factors for the accumulation of phosphorites is the high rate of weathering and inputs of P from continents to oceans (Filipelli, 2011). Other factors that are involved in these changing environments include climatic changes as glaciations, increased riverine P fluxes from land to sea, changing ocean currents, and upwelling patterns as a reflection of the configurations of plates and plate movements, affecting global seawater levels and increasing biological productivity, for example (Sheldon, 1980; Föllmi, 1996; van Straaten, 2007; Filipelli, 2011). Complex biogeochemical and biophysical processes



**Figure 1.** Graph showing: Left, distribution of major phosphate abundances and number of phosphorous deposits over time; Center, volume of phosphate ore; and Right, number of deposits. Source: Cook & McElhinny (1979).

lead to sedimentary P accumulations in shallow marine environments, and these sedimentary phosphates accumulate when eroded-P laden sediments are transported from land to sea and sedimented close to shorelines, e.g., in estuaries (Föllmi, 1996; van Straaten, 2007; Filipelli, 2011). The subsequent accumulation processes, including the microbial breakdown of buried organic matter, oceanographic conditions for winnowing, and concentration were reviewed by Föllmi (1996) and Filipelli (2011).

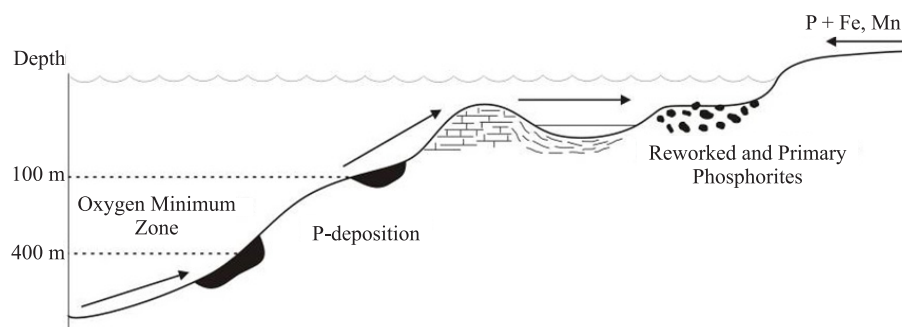
Geologists have sought to find out which factors were responsible for the global, regional, and local changes that prompted the accumulations of phosphate rock, and many researchers have documented the changing weathering environments due to climate changes and P accumulation, as illustrated in the reviews by Föllmi (1995, 1996), Delaney (1998), Filipelli (2011), and Pufahl & Groat (2017). Local factors like source proximity, changing weathering and sediment accumulation rates, water depth, current directions, local obstacles, oxygen content, and biological accumulation rates contribute to the accumulation of phosphate minerals in shallow marine sediments (Föllmi, 1996; van Straaten, 2007; Filipelli, 2011). A simplified sedimentological model of phosphorite distribution on shallow marine shelves is shown in Figure 2.

Sedimentary phosphate accumulations occur in but are not restricted to the Phanerozoic period. Although fewer in number, phosphate deposits are also found in the Precambrian, showing patterns of spatial and temporal distributions reflecting environmental changes. For example, Papineau (2010) documents the effects of changing climatic conditions, net primary productivity, oxygenation state of the atmosphere,

changes to seawater nutrient inputs, biological activity, and oceanographic changes on phosphate accumulation in the Precambrian, specifically at both ends of the Proterozoic period, i.e., the early Paleoproterozoic and the Neoproterozoic (Figure 3). Valuable information on global phosphate deposits have been compiled in three volumes edited by Cook & Shergold (1986), Notholt et al. (1989), and Burnett & Riggs (1990). In addition, information on the geology of selected phosphate deposits and on how to find new P resources are described in van Straaten (2007).

Another major type of phosphate accumulation is related to igneous carbonatite complexes that intruded the Earth's crust in specific geological geotectonic environments and during specific time periods. Carbonatites have been studied for many decades, mainly for their interesting petrogenesis and geochemical and petrological complexities (Brod et al., 2000; van Straaten, 2007; Simandl & Paradis, 2018). From an economic point of view, carbonatite complexes are explored for: their economic accumulation of P, for agriculture; rare earth elements, for electronic appliances and magnets; and niobium, for the production of special stainless steel (Simandl & Paradis, 2018). The main agrominerals found in carbonatites include phosphates (mainly apatite), phlogopite, and vermiculite sources, as well as the carbonate minerals calcite and dolomite (van Straaten, 1989, 2007; Simandl & Paradis, 2018).

Carbonatites and associated alkaline rocks are thought to have developed from deep mantle plumes that penetrate the continental lithosphere (Bell & Simonetti, 1996) or, alternatively, by the emplacement in continental extensional settings, in reactivation



**Figure 2.** Simplified sedimentological model of the main phosphorite distribution in a continental shelf environment. Source: van Straaten (2007).

zones of structural weakness and extension, such as rift valleys, shear zones (Woolley & Bailey, 2012; van Straaten, 1989), or surrounding large-scale sedimentary basin zones, being associated with Large Igneous Provinces (LIPs) (Ernst & Bell, 2010). Examples from Brazil, like the Paraná-Etendeka province, support the interpretation of carbonatite alkaline complexes associated with LIPs (Brod et al., 2000; Gibson et al., 2006; Ernst & Bell, 2010; Rosetti et al., 2018), and also with tectonic domes (crustal arches) and lineaments (Gomes et al., 2011).

The most known carbonatite complexes were emplaced during specific time periods of structural reactivation, specifically in crustal extensional settings. Woolley & Bailey (2012) describe five “episodes” of carbonatite emplacement worldwide. Van Straaten (1989) highlights the following three major periods of carbonatite-alkaline intrusive phases in Eastern and Central Africa: Later Proterozoic from 750–680 Ma, Cretaceous from 120–100 Ma, and Cenozoic from 40–0 Ma. Some of these carbonatite-alkaline periods of emplacement, as, for example, the Cretaceous carbonatite-alkaline magmatism, have also been observed in Brazil, as well as across the Atlantic in Angola and Namibia (Comin-Chiaramonti et al., 2007).

Carbonatites contain variable amounts of Ca phosphate (apatite), whose most concentrated forms are found as residual concentrations in the weathered zone above carbonatites (van Straaten, 2007; Simandl

& Paradis, 2018). The ages of the primary phosphate-bearing carbonatites range from the Archean to the Phanerozoic. A database on carbonatite complexes worldwide has been compiled by Woolley & Kjarsgaard (2008), who, at the time, reported 527 carbonatite occurrences. In a recent comprehensive review on carbonatites, Simandl & Paradis (2018) discussed carbonatite genesis, resources, modes of emplacement, and exploration.

Regarding potassium, the mineral occurs at high concentrations in K salts, as potash (KCl), and other salts formed from evaporating sea water in restricted basins and from saturated brines in terrestrial environments (Blatt et al., 2006; van Straaten, 2007). It occurs in salt basins of different sizes, ranging from terrestrial and small salt basins of a few square kilometers to continent-wide salt basins with areal extends of several thousand square kilometers (Blatt et al., 2006). K-salt deposits are found in continental rifts, e.g., the Upper Rhine Graben, and in rifts that precede the opening of new oceans. Potash deposits may occur in passive continental margin zones, e.g., on the continental margins of West Africa and Brazil, and in late-orogenic foreland basins, such as the Carpathian foredeep (van Straaten, 2007). The most voluminous deposits of potash, however, are observed in large-scale extensive epicontinental basins like those in Russia, Belarus, North America, and central Europe.

Salt deposits are concentrates caused by sea water evaporation in hot dry climates in restricted basins,



**Figure 3.** Precambrian phosphate rocks: Left, Paleoproterozoic sedimentary phosphate rocks in Jamakhottra, India, with deformed phosphatic stromatolites, in a dolomitic matrix; and Right, Neoproterozoic folded phosphates of the Bambui Group, in the Rocinha mine, Brazil, with a pen used as a scale. Photos taken by the author.

over long periods of time (Blatt et al., 2006; van Straaten, 2007). The distribution of salt deposits is not only controlled by climatic conditions during Earth's history but also by spatial factors, specifically tectonic settings, including the formation of continental rifts, the opening of marine rifts, and the opening of marine basins related to the formation of mountain belts or large-scale inter-continental basins (Hardie, 1996).

Although some traces of evaporites are reported from Precambrian rock formations, the preservation of salt deposits, including those of K salt, increased from the Cambrian to Recent era. Moreover, the salinity and chemical composition of sea water changed over geological time (Hardie, 1996; Lowenstein et al., 2003), affecting the formation of salts, including K-bearing ones. Warren (1999, 2006) provides detailed information of the origin, evolution, and economic importance of evaporite deposits around the world. It should be noted that evaporite basins and associated K-salt deposits are not only sources of K but also of salts that contain Mg and other agromineral resources, such as kieserite ( $\text{MgSO}_4 \cdot \text{H}_2\text{O}$ ) and gypsum, respectively (van Straaten, 2007).

## 5. Agromineral resources in plate tectonic settings

Over the past hundred years, geoscientists have unraveled the structure of the Earth and found that its upper portion, the lithosphere, which consists of the upper mantle and crust, is relatively rigid and brittle, moving on the underlying warmer, more plastic portion of the mantle, the asthenosphere (Skinner & Porter, 1995; Condie, 2005). In the 1960s, scientists started to understand how large rigid portions of the lithosphere, known as plates, moved over the asthenosphere and relative to each other (Skinner & Porter, 1995; Condie, 2005). While plates move relative to each other and relative to the underlying asthenosphere, their internal structure remains largely intact and rigid, with deformation taking place mainly along plate boundaries, but also in brittle intraplate structural zones (Skinner & Porter, 1995; Condie, 2005).

There are three types of plate boundaries: divergent plate boundaries, where plates move apart from each other; convergent plates, where plates move towards each other; and transform plate boundaries, where plates slip laterally past each other (Skinner & Porter,

1995; Condie, 2005). The understanding of the dynamic movement of these rigid plates started from research on seafloor spreading, which led to the concept of plate tectonics (Dietz, 1961; Hess, 1962; Isacks et al., 1968; Le Pichon, 1968; Dewey & Bird, 1970; Dewey, 1972). The tectonic evolution of the Earth since about 4.4 billion years has changed due to variations in geothermal gradients, size, composition, and structural set up of the lithosphere and the geometry of continental plates, as well as to the development of the atmosphere and biosphere (Skinner & Porter 1995; Condie, 2005).

Some scientists relate climate change events with plate tectonic movements. Since the solid Earth surface is in direct contact with the atmosphere and oceans, any major change in the configurations of the continental plates can have consequences on atmospheric circulation and ocean currents (Skinner & Porter, 1995). Hay (1996) and Ruddiman (1997) outlined the physical effects of plate tectonics on climate change and described the complex inter-relationships of plate tectonics and mountain formation and uplift, with resultant climate changes, increased weathering rates, and direct and indirect effects on biogeochemical and biological systems on land and in the sea.

The plate tectonic concept, now widely accepted, brought together a new and comprehensive interpretation of the make-up and dynamic development of the upper skin of the Earth. Here, this knowledge of plate movements will be used to piece together the puzzle of the distribution of agromineral resources in space and time.

The general spatial and temporal distribution of sedimentary and igneous rocks in the plate tectonic framework will provide some insight into the conditions and processes of agromineral resource concentration and accumulation, and may also provide some guidance in the exploration of new agromineral resources.

### 5.1 Agromineral resources formed at convergent plate boundaries

Widespread volcanic activities and earthquakes characterize modern convergent plate boundaries. There are three principal settings of convergent plate boundaries: plate margins where the oceanic lithosphere sinks beneath an overriding plate of the

continental lithosphere, plate margins where the oceanic lithosphere sinks beneath an overriding plate of another oceanic lithosphere, and collision zones between two continental plates (Skinner & Porter, 1995). Examples are: western South America, for oceanic plate sinks under a continental plate; Indonesia, for oceanic plate sinks under another oceanic plate; and the Alps and the Himalayas, for collision between two continental plates.

In the following sections, the three major convergent plate boundaries are described, with added information on their agromineral resource potential.

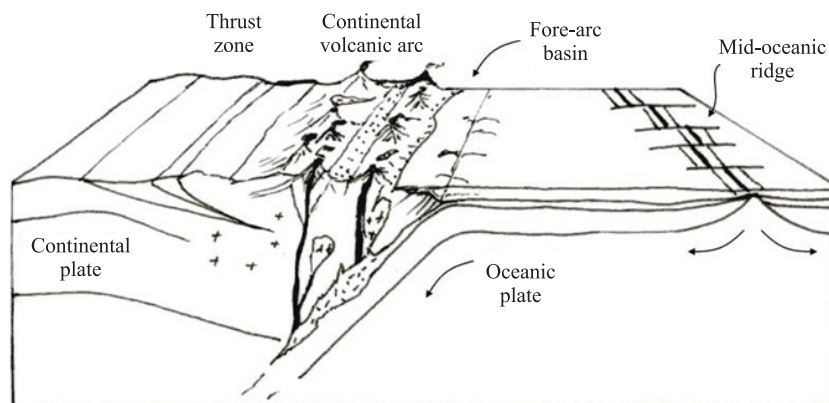
## 5.2 Agromineral resources associated with convergent plate boundaries between oceanic and continental plates: continental volcanic arcs

Mountain ranges with continental volcanic arcs are formed at convergent plate boundaries between oceanic and continental plates (Skinner & Porter, 1995; Condie, 2005). At this convergent boundary, the oceanic plate sinks below a continental plate in an inclined zone, called a subduction zone (Figure 4). When the subducted plate is starting to melt at depth, magma is formed, ascending through the overlying plate to the surface; however, some magma does not reach the surface and forms intrusive bodies in the overlying continental plate (Skinner & Porter, 1995; Condie, 2005).

Continental volcanic arcs develop from eruptive volcanoes with different kinds of magmas, and lavas and tuffs with andesitic composition being the most

common volcanics in this environment; andesitic volcanics are derived from magma that has undergone fractional crystallization or is mixed with materials from the continental crust (Skinner & Porter, 1995; Gill, 2010). Basaltic rock and rhyolites can also be found in this environment. Basaltic magmas may rise directly from the subducted oceanic plate and extrude, whereas silica-rich rhyolites may erupt from magma that has formed from the partial melting of the continental crust (Condie, 2005; Gill, 2010). Agrominerals, such as volcanogenic sulfur, perlite, pumice, and silicon-rich zeolites, are found in areas with rhyolites and with silicic explosive volcanics (Mason et al., 2004).

This geological setting is a zone of considerable agromineral wealth of both sedimentary and volcanic origin, as well as of a fresh new rock derived from the action of subduction. The Cordillera of Canada and the United States provides a wide spectrum of agromineral wealth, ranging from sedimentary phosphate rocks in the western United States to voluminous shallow water carbonates and various agromineral resources associated with convergent plate margin volcanism, such as perlite, pumice, and zeolites. Mathers (1992) describes some of the agromineral resource potentials in Central America. In South America, apart from various sedimentary phosphate rock deposits, there are also large nitrate deposits in northern Chile (Böhlke & Revesz, 1997); however, these deposits are not related to a specific plate tectonic setting but are results of hyper-arid climatic conditions. Furthermore, very few igneous phosphate occurrences related to carbonatites and no K salts of epicontinental origin are found in this geotectonic environment.



**Figure 4.** Schematic diagram illustrating a converging oceanic plate, which bends and sinks under a continental plate.



Two types of agromineral resources are predominant in this convergent plate environment: volcanogenic agrominerals, such as volcanogenic sulfur, perlite, pumice, and Si-rich zeolites; and sedimentary agrominerals, including nitrates, phosphorites, carbonates, and borates. The rock types cover a range of volcanic extrusive rocks, from basalts to andesites to rhyolites.

### 5.3 Agromineral resources at convergent plate boundaries between oceanic plates: volcanic island arcs

Volcanic island arcs are formed at convergent plate boundaries between oceanic lithospheres: the oceanic plate sinks, in a subduction zone, below another oceanic plate (Skinner & Porter, 1995; Condie, 2005).

In the process, volcanoes start to build on the ocean floor and develop into volcanic arc islands (Figure 5).

Volcanic island arcs, as well as back arc basins, are found in many areas around the Pacific, as, for example, in the Philippines, Japan, Indonesia, and Aleutian Island in Alaska (Skinner & Porter, 1995; Blatt et al., 2006). Figure 6 illustrates an active island arc with a trench, accretionary wedge, and fore-arc basin at the front of the arc, besides marginal seas behind the volcanic arc, known as back-arc basins, which exhibit structural pull-apart characteristics with stretched basins. The agrominerals found in this setting are also shown.

The diversity of agromineral resources in this geotectonic setting is high, with occurrences of both sedimentary and volcanic-related agrogeological resources. The sedimentary agromineral resources

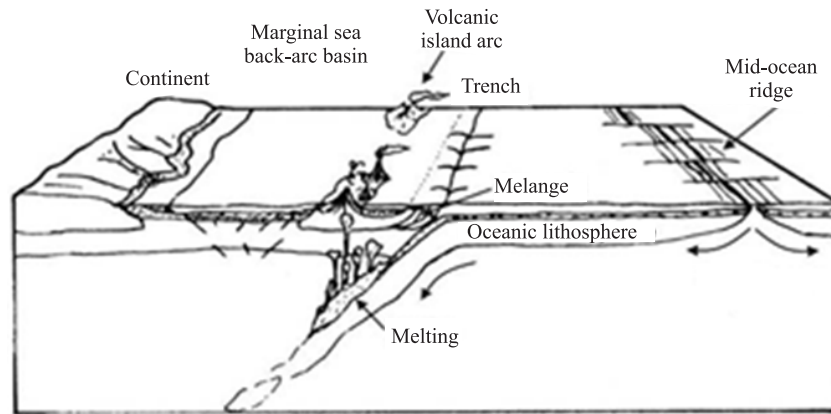


Figure 5. Schematic diagram of a converging oceanic plate, which bends and sinks under another oceanic plate.

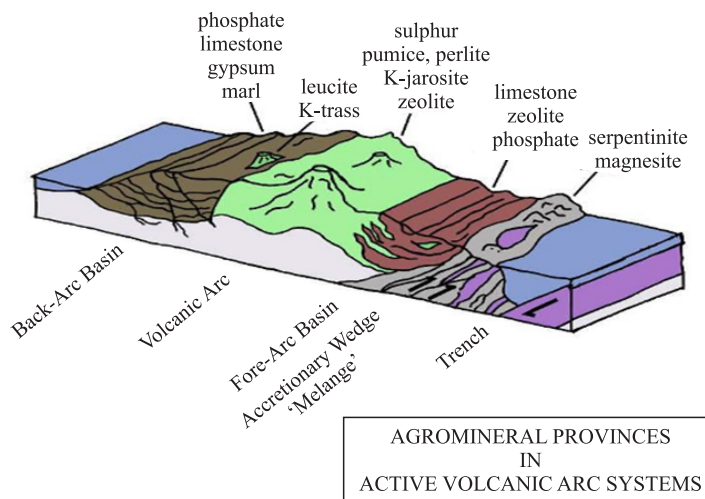


Figure 6. Simplified model of agromineral distribution in a volcanic arc setting in Java, Indonesia.

found in the fore-arc basin include phosphate rocks (when ocean circulation and upwelling zones coincide with the plate boundary), as well carbonate sediments (van Straaten, 2007). In the volcanic environment, it is possible to find elemental volcanogenic sulfur, zeolites, pumice, and perlite, besides trace elements like Cu, Mo, and Zn (van Straaten, 2007). In the pull-apart back-arc environment, carbonates and evaporites and gypsum can also be observed (Blatt et al., 2006). Agromineral resources for direct application include basalts and K-bearing volcanics furthest away from the subduction zone.

#### 5.4 Agromineral resources at convergent plate boundaries where continental plates collide

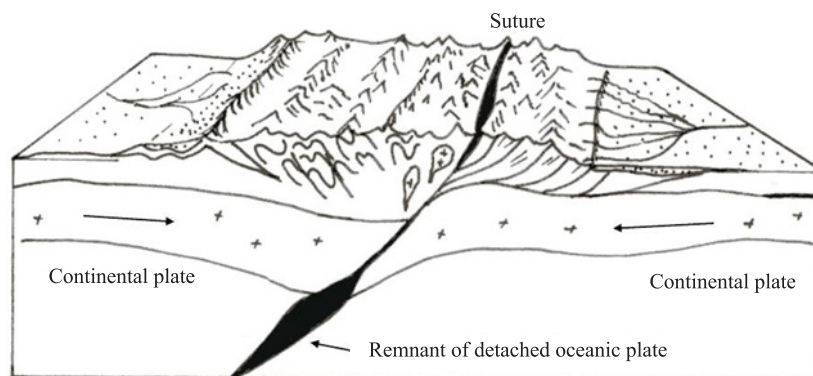
Convergent plate boundaries occur where two continental plates have collided (Skinner & Porter, 1995; Condie, 2005). An example is the collision of the Indian plate and the Eurasian plate that formed the Himalayas (Figure 7).

In this geotectonic setting, mainly sedimentary agrominerals, such as carbonates and metamorphic rocks of different compositions, are found, but also a few volcanic rocks. Moreover, highly deformed and altered remnants of the oceanic crust occur in the suture zones, where ultramafic rocks, partially altered to serpentinites, are often verified (Condie, 2005). Due to the lack of young volcanic activities and addition of a fresh new rock from the lithosphere, the agromineral resource diversity and wealth in these settings is restricted to metamorphic and sedimentary

rocks, such as carbonates and sulfates, and, in some places, to sedimentary phosphate rocks (phosphorites), as, for example, the Purulia phosphorites of India (van Straaten, 2007).

#### 5.5 Agromineral resources associated with oceanic plates and with oceanic and continental mantle plumes

The oceanic crust forms at diverging plate margins at mid-ocean ridges where magma from the mantle rises to the surface (Skinner & Porter, 1995; Condie, 2005; Gill, 2010). The solidified magma in the form of gabbro and basaltic lava is gradually pushed away from the ridges by the newly formed oceanic crust, and, because of this continuous lateral movement, the sea floor is youngest at the site of the mid-ocean ridge and progressively older further away (Skinner & Porter, 1995; Condie, 2005; Gill, 2010). In the case of South America and Africa, the oldest ocean crust occurs below the passive margin sediments on both sides of the ocean, at the margins of these continents (van Straaten, 2007). The oceanic crust is 5–8 km thick and is composed of gabbro and basalt overlain by a thin veneer of deep-water sediments, mainly fine mud and siliceous ooze (Blatt et al., 2006; Condie, 2005). The areal extent of the oceanic crust is very large as it underlies large parts of the abyssal plains of the oceans. On large areas of the ocean floor, ferro-manganese nodules have accumulated, containing considerable amounts of Co, Cu, and Ni (Heath, 1981). However, in the current topographical setting, the ocean crust



**Figure 7.** Schematic diagram of a fold belt of a collision zone between two continental plates. Remnants of the detached oceanic plate or the mantle are shown in the suture zone. Continent to continent collision zones are represented by the Alps and Himalayas.

and the sediments that cover it are of no agrogeological significance as they are submerged.

“Hot-spot” volcanoes develop above hot rock mantle plumes that have risen from the core-mantle boundary or from the base of the lithosphere, which was partially melted by the rising mantle plumes (Morgan, 1972; Courtillot et al., 2003). In oceanic plate settings, basaltic magma that formed at the base of the lithosphere rises directly to the surface of the oceanic lithosphere. Typical hot-spot volcanoes in oceanic environments are the Hawaii Islands in the Pacific (Tarduno, 2007), as well as the Reunion Islands and Kerguelen in the Indian Ocean (Coffin & Eldholm, 1993). In a continental plate setting, these volcanoes are found in the Snake River Plain in the Yellowstone area of northwestern United States (Mason et al., 2004; Smith et al., 2009). Since the locations of the hot spots remain more or less constant but the plates above them move, it is possible to track the movement of the oceanic and continental crusts above them through “hot-spot tracks”. Although the main compositional types of volcanoes over hot spots are basalts and rhyolites (rarely andesites), mafic potassic volcanism is also observed in several locations (Gibson et al., 1995).

In terms of agromineral abundance, however, these areas are poor as only volcanic-related agrominerals are found in them. In silicic volcanic areas, agrominerals such as silica-rich perlite and pumice, as well as Si-rich zeolites, are common. The volcanic rocks overlying the

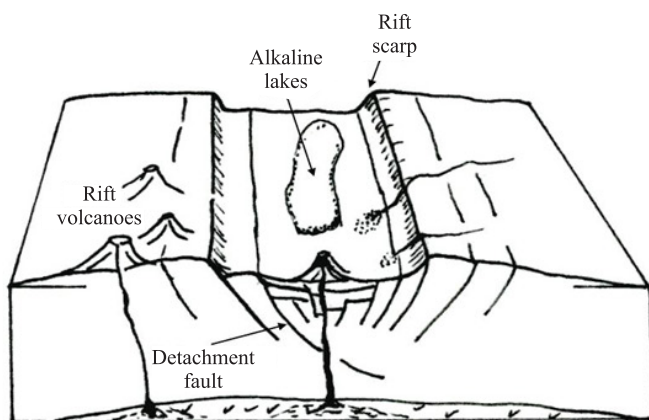
Trindade mantle plume in Brazil are characterized by high K, Mg, and P concentrations (Gibson et al., 1995).

## 5.6 Agromineral resources found in diverging plate boundary zones in continental rifts

Continental rifts are linear belts in a continental setting in which the continental crust is pulled apart (Skinner & Porter, 1995; Condie, 2005). These divergent, “pull-apart” structures are the result of lithospheric stretching and the start of a break-up of a continent. While the upper part of the cold and brittle crust breaks up into sets of linear faults, the center of the structure forms long linear trough-like feature, rifts or grabens, in which sediments accumulate (Skinner & Porter, 1995; Condie, 2005). Examples of rifts in continental settings include the East African Rift system, the Baikal rift in Asia, the Upper Rhine graben in central Europe, and the Basin and Range in the United States.

The type of volcanism along rift structures varies from basaltic to rhyolitic, but many alkali-rich volcanic varieties are also common (Rosenthal et al., 2009). Unique, but typical for this setting, are igneous alkaline rocks, including ultrapotassic volcanics and carbonatites that occur along rift faults and deep structural fault zones (Figure 8).

In this geological setting, agromineral resource wealth is high. The carbonatites along the East African rift structures contain valuable agromineral accumulations, including phosphates, carbonates,



**Figure 8.** Schematic diagram of: Right, continental rift; and Left, kamafugite quarry in Bunyaruguru, Western Uganda. Photo taken by the author.

vermiculite, and economic concentrations of copper in some carbonatite intrusions as in Phalaborwa in South Africa (van Straaten, 2007).

When seawater enters the rift system, followed by a period of high evaporation, large linear salt basins develop, some of them containing K salts, as, for example, the rift depressions of Ethiopia-Eritrea and the Rhine graben (Blatt et al., 2006; van Straaten, 2007). In the rift environments, the volcanic agrominerals found include pumice, perlite, and zeolites, and the volcanic rocks may be potassic, even ultrapotassic, as, for example, the kamafugites in the Western Rift of Uganda (Rosenthal et al., 2009).

### 5.7 Agromineral resources within continental plates in shield areas

The continental lithosphere is made up of structurally stable areas that have not been affected by mountain forming activities over the last 1 billion years or so, that is, these areas have been eroded over millions of years, have cooled down, and are structurally brittle, being predominantly made up of metamorphosed and igneous rocks. In typical shield areas, igneous and metamorphic rocks, including those of older orogenies, crop out at Earth's surface, being represented as mobile belts (Condie, 2005). In stable cratonic areas, the Precambrian shield is found in sites overlain by cover formations of Phanerozoic rocks.

Dolerite dikes that cut across these vast "seas" of granites and gneisses provide some additional nutrient sources. In addition, greenstone belts, which are old remnants of oceanic crust and volcanic arcs, provide environments for better plant growth in these largely granitic shield areas. However, the granite-dominated

parts of the shield area are generally quite devoid of agrominerals.

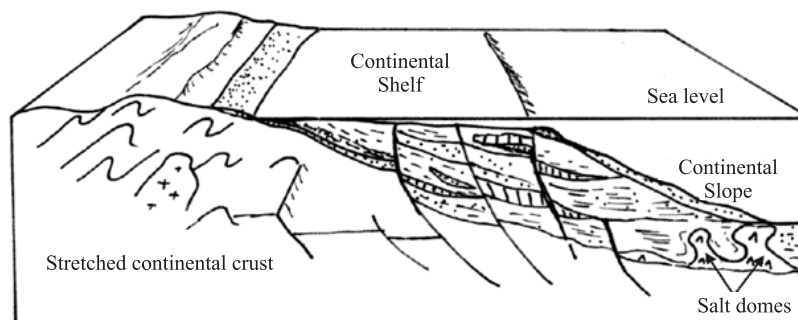
When granite and metamorphic rocks are subjected to broad gradual structural warping, regional basins, filled with shallow water sediments, are formed (Blatt et al., 2006). It is in these large regional basins where carbonates, sulfates, and epicontinental salts precipitate, forming agromineral deposits, such as carbonates, sulfates, and evaporites, including K salts.

As previously mentioned, in general, the geodiversity and agromineral resource base in typical granite-dominated shield areas is relatively low. However, the mobile belts in shield areas, with metamorphosed or unmetamorphosed sediments, can provide substantial agromineral resources, such as carbonates and, in some specific sites, "old" phosphate rocks.

### 5.8 Agromineral resources in nonvolcanic passive margin sediments

Thick piles of sediments, deriving from continents and shallow water environments, accumulated at tectonically inactive boundary zones between continental and oceanic crusts (Figure 9). Known as passive margin sediments, they are found on continental shelves at the inactive boundary (no recent volcanic activities, very few earthquakes) between the stretched continental crust and the ocean crust.

Passive margins started to develop when continents pulled apart and broke up, formed rifts, and then drifted apart. When continents break up, the first sediments to be deposited in the stretched basins and rifts along the continents are nonmarine sands and mudstones, followed by sediments formed in shallow marine waters (Blatt et al., 2006). In hot climates, the



**Figure 9.** Schematic diagram of a nonvolcanic passive margin setting.

seawater in isolated basins periodically evaporated to form thick deposits of carbonates, sulfates, and salts (Blatt et al., 2006). In many passive margin environments, accumulations of carbonates, gypsum, and anhydrite, as well as K-salts, are reported (Blatt et al., 2006). Fine-grained sedimentary K silicates, like glauconites, are typical sediments in these areas (Van Houten & Purucker, 1984).

The geodiversity in this environment, which is largely free of volcanic rocks, is generally rich in sedimentary agrogeological resources, including limestones, dolostones, gypsum, K salts, and K silicates as glauconitic sediments. When the global ocean current and global ocean basin configurations were favourable for the upwelling of cold nutrient-rich waters, marine phosphate rock deposits were also verified in these environments (van Straaten, 2007). In periods of global sea level rises, glauconite accumulations are typical for passive margin settings (Van Houten & Purucker, 1984).

Among the agromineral resources with specific spatial and temporal distribution patterns, stand out sedimentary sandy rocks that contain green-coloured glauconite minerals, iron-rich, and K-bearing sheet silicates, which are often called “greensands” (Heckman & Tedrow, 2004). Spatially, glauconite-bearing sediments occur in marine environments, in areas with low sedimentation rates, particularly on modern continental shelf/slope transitions, at 50–500 m depth (Amorosi, 1997). Glauconitic minerals in continental slope positions are often spatially associated with phosphate minerals (Burnett, 1980; Carson & Crowley, 1993). Since glauconite and phosphate minerals occur frequently in close proximity, glauconite is often used as a pathfinder for phosphate accumulations. In terms of temporary distribution, glauconitic sediments occur in predominantly marine sediments of Cretaceous, Tertiary, and Recent ages; however, glauconitic marine sediments are also found in Precambrian rocks in, for example, India (Chaudhuri et al., 1994; Rawlley, 1994; Banerjee et al., 2008), Brazil (Guimarães et al., 2000), and several other countries (Van Houten & Purucker, 1984; Dooley, 2006).

## 6. Agromineral resources as directly applied soil remineralizers

The classical agrogeological research on the application of finely ground rocks on soils was pioneered by Hensel (1894), who wrote the classic

book: “Bread from Stones”. Later, Keller (1948), Fyfe et al. (1983), Chesworth (1982), Leonardos et al. (1987, 2000), Chesworth et al. (1989), Theodoro & Leonardos (2006), van Straaten (2006, 2007), and others continued studying the direct application of suitable agromineral resources to remineralize and improve the productivity of soils, especially by small-holder farmers.

Agromineral resources for direct application include finely ground volcanic rocks, such as basalts, phonolites, kamafugites, and other nutrient-rich volcanic rocks, as well as certain metamorphic and sedimentary rocks that can enhance soil productivity. However, this review paper will concentrate on the potential use of basaltic rock coproducts in agriculture, on a global scale. Why focus on basalt for present and future research? While there are many igneous rocks that have local and regional importance as agrominerals for direct application, basalts are found in large volumes on all continents in almost every country of the world, so there is no risk of their exhaustion. Basalts are commonly extracted for use as aggregates in the construction industry and as a component in the production of asphalt, although the fine-sized aggregates are often discarded as wastes or rejects. Globally, basalts are the most common soil amendments with multi-nutrient potential and that are readily available, since they were already extracted for another purpose.

Finely ground basalt has been successfully tested and applied as an agromineral in temperate climates in countries like Canada and Germany, as well as in tropical climates in Malaysia, Brazil, and tropical parts of Australia, for example (Gillman et al., 2002; Anda et al., 2009, 2015). The main effects of applying finely ground, especially glass-rich basalt to highly depleted tropical soils include: small increases in pH (liming effect); reduction of Al toxicity; increase in cation exchange capacity; release of Ca, Mg, Fe, and K; and, in some cases, such as in Australia, increased P availability (Coventry et al., 2001).

Geologically, basalt rocks are found and extracted in many geological settings, on all continents and in virtually all geological time spans. These basalts may occur: related to mantle plumes, in subduction zones, in basaltic provinces in continental rift zones, in mid-ocean ridges, in oceanic islands as volcanism in Precambrian granite-greenstone terrains, and in “mobile belts”, as will be further detailed.

For basalts related to mantle plumes, basaltic magma is derived from the upwelling of hot rocks within the mantle of the Earth. LIPs consist of voluminous flood basalts and their associated plumbing systems, e.g., radiating mafic ring dykes (Coffin & Eldholm, 1993). LIPs are high-volume, short-duration, and intraplate magmatic events consisting primarily of voluminous flood basalts (Coffin & Eldholm, 1994; Ernst et al., 2005). Examples of these voluminous LIPs include the c.65-million-year-old Deccan Traps in India (volume > 1 million km<sup>3</sup>), the c.134-million-year-old Paraná-Etendeka flood basalt province of the Serra Geral Group in Brazil (volume >600.000 km<sup>3</sup>), and the 250-million-year-old Siberian Traps (volume >4 million km<sup>3</sup>).

In subduction zones, basalts are integral parts of the volcanism related to converging plate margins (Skinner & Porter, 1995; Condie, 2005; Gill, 2010). They are common rock types, together with andesites and rhyolites, found in active continental margin arc and in island arc environments.

Basaltic provinces in continental rift zones are widespread, with voluminous basaltic lavas occurring, for example, in the Ethiopia-Kenya volcanic provinces (MacDonald et al., 2001).

Mid-ocean ridge basalts are formed under water, along extensive linear mid-ocean ridge environments (Condie, 2005; Gill, 2010). However, outcrops of this underwater

mountain system are rare to find as most of the magmatic activity takes place below the water surface.

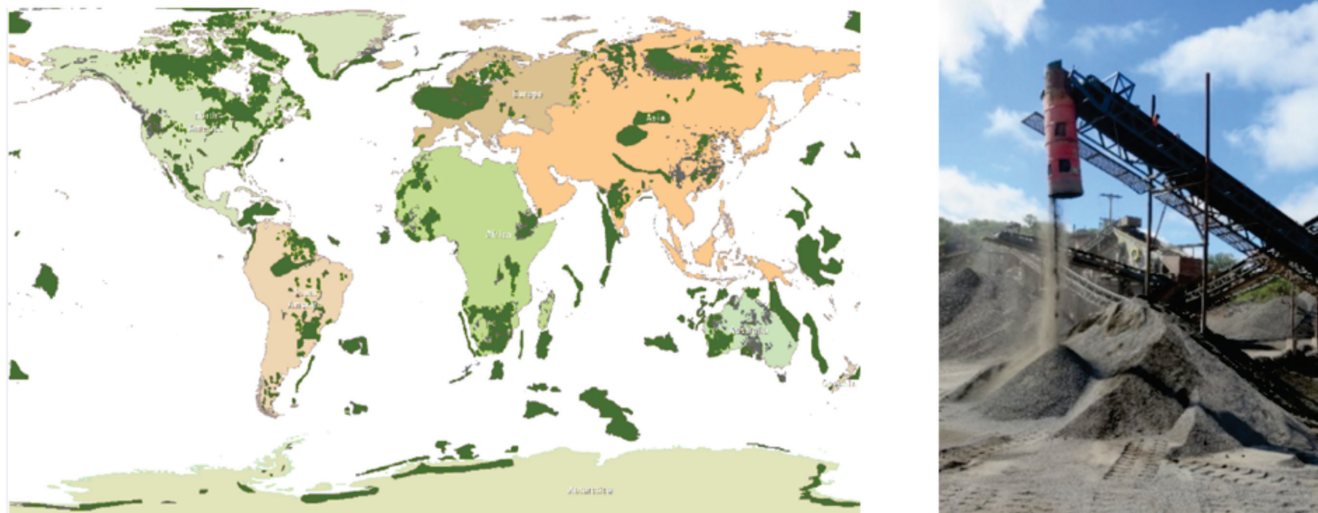
Another type of basalt is that of oceanic islands, found mainly on volcanic islands on the oceanic crust (Condie, 2005; Gill, 2010).

Basalt volcanism in Precambrian granite-greenstone terrains are common in many shield areas; “greenstones” are a succession of rocks that contain >50% volcanic and volcano-sedimentary rocks (Condie, 1981, 2005).

Basalts in “mobile belts” are also widely found in Precambrian terranes, as part of previous orogenic activities (Condie, 1981, 2005). Many of these basalts are deformed and, in some cases, metamorphosed or hydrothermally altered.

### 6.1 Basalt, a common agromineral resource for soil remineralization

As previously described, basalt rocks are found in several environments and on all continents (Figure 10). Therefore, the resource base of basalts worldwide is virtually inexhaustible. At present, basalt resources are widely extracted industrially and used primarily as aggregates for the construction industry. However, during the extraction and comminution of these resources in quarries of different sizes, there are some proportions discarded as wastes, called “the fines”, which can be used successfully for agriculture.



**Figure 10.** Left: Global distribution of Large Igneous Provinces, including massive flood basalts (courtesy R. Ernst); and Right: typical basalt quarry, showing the separation of different sizes of crushed basalt, including fines, which can be used, after further fine grinding, for direct agricultural application on highly nutrient-depleted soils. Photo taken by the author.

Finely ground basalt is already effectively used as a soil amendment in Australia (Gillman et al., 2002) and Malaysia (Anda et al., 2009, 2015). The young basalt used is olivine rich and contains a high quantity of volcanic glass. In existing quarries, where basalt is extracted for use as an aggregate in the construction industry and as a component in asphalt production, basalt fines are ground further to  $<250\ \mu\text{m}$  and, as a by-product, are used as a resource, not as a waste (Figure 10). Results of the use of these basalt fines in the tropical agriculture of northeastern Australia are detailed in Coventry et al. (2001) and Gillman et al. (2002). From an agronomic and mineralogical point of view, it seems that relatively young (Tertiary and younger) and olivine- and volcanic-glass-rich basalts have the highest potential as soil amendments. It should be stressed that the use of basalt from existing quarries is also resource efficient, meaning there is no need for the opening of new quarries or mines.

Moreover, the application of finely ground basalt has been advocated in recent years as a medium to sequester  $\text{CO}_2$  through the process of “enhanced weathering”, a potential co-benefit of extracting and using basaltic agromineral resources (Beerling et al., 2018).

## **7. Nutrient sources from agrogeological resources and their geological/geotectonic settings**

### **Nitrogen**

Nitrogen occurs as nitrate in specific climatically controlled and extremely arid environments, such as inland, off the Humboldt Current coast of Chile (Ericksen, 1983; van Straaten, 2007). Nitrates from this county are widely used in the horticultural industry.

### **Phosphorus in sedimentary rocks**

Sedimentary phosphate rocks, also called phosphorites (with  $>15\% \text{P}_2\text{O}_5$ ), occur in shallow marine environments (Cook & McElhinny, 1979; van Straaten, 2007). Phosphate accumulation is controlled by changing water levels, inputs from land to sea (estuaries), accumulation of organic matter (black shales), and upwelling systems (Cook & McElhinny,

1979; van Straaten, 2007). However, sedimentary phosphate accumulations occur in specific sedimentologically controlled areas, called phosphate provinces and phosphatic epochs, from the Proterozoic to Recent era (Cook & McElhinny, 1979; van Straaten, 2007). Sizeable phosphate rock accumulations are known from the Paleoproterozoic, Neoproterozoic/Cambrian, Ordovician, Permian, Jurassic, Cretaceous, Eocene, and Miocene (Cook & McElhinny, 1979). Plate tectonics – with settings related to both active and passive plate margins – play a major role in the redistribution of continental and oceanic plates, which influences the configuration of land and sea, caused by the shifting, moving, breaking up, and uplifting of continental plates (Skinner & Porter, 1995; Condie, 2005; Gill, 2010). In recent years, Föllmi (1996) and Filipelli (2011) stressed the importance of changes related to the uplifting of plates that control weathering rates and P inputs from land to sea. Sedimentary phosphates are widely used, either as conventional, highly soluble P fertilizers, such as single and triple superphosphate, after being further processed, or as a low-cost fertilizer for direct application (van Straaten, 2007; Simandl & Paradis, 2018).

### **Phosphorus from igneous phosphate rock resources**

Deposits of igneous phosphate rocks, mainly used for the production of P fertilizers, are primarily associated with carbonatites or nepheline-syenite complexes (van Straaten, 2007; Simandl & Paradis, 2018). Many phosphate accumulations occur in the weathering environment as residual phosphates overlying carbonatite complexes. In terms of plate tectonic settings, most carbonatites are found in divergent intraplate settings, as, for example, rifts, or are associated with deep-seated structural weaknesses of the lithosphere (Woolley & Bailey, 2012). Carbonatites have also been linked to the emplacement of mantle plume-related LIPs, and are thought to be located at the outer, cooler edges of mantle plumes, following, in an “opportunistic” manner, existing faults and structural zones of weaknesses in the lithosphere (Ernst & Bell, 2010).

## Potassium

Potash is a term that encompasses a variety of mined and industrially-manufactured salts that contain K in water-soluble form (van Straaten, 2007). Globally, potash resources occur as potassium salts, mainly K chlorides (KCl) and sulfates, in evaporite sequences in sedimentary basins (Blatt et al., 2006; van Straaten, 2007). The main types of potash-bearing salt deposits are strata-bound, flat-lying or deformed, although, in some places, K-bearing brines are also extracted (Blatt et al., 2006).

Potash deposits occur primarily in intracratonic basins, continental rift and marine rift environments, as well as in foreland basins. In terms of plate tectonics, potash deposits are reported in extensional intraplate environments and in continental passive margins, e.g., in the South Atlantic salt basins (Kukla et al., 2018). Potash is widely used as part of N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O fertilizers, and some P salts are also allowed in organic agriculture (Havlin et al., 2013).

Another form of K deposit is associated with both igneous and sedimentary K silicates. Silicate K accumulation is observed in some igneous, K-rich phonolites, as verified in Poços de Caldas in Brazil, and in sedimentary, glauconite deposits – typical passive margin deposits – of different ages (Schorscher & Shea, 1992; Amorosi, 1997). From a plate tectonics model point of view, igneous K-silicate deposits, like K phonolites, occur in extensional continental intraplate environments, similar to carbonatite environments; in some parts of the world, e.g., Brazil, phonolites are used as a direct-application K fertilizer. Furthermore, K-bearing biotite mica schists are widely found in metamorphic terranes.

Glauconite is often reported in association with sedimentary phosphates. In Brazil, glauconite deposits, known as “verdete”, are partially processed and applied to various crops, such as coffee (Dias et al., 2018). However, new research is under way towards concentrating K mica, specifically biotite, from granite wastes for application on various crops (verbal information)<sup>1</sup>.

<sup>1</sup> Mr. Tomas Teodoro da Cruz, Mining Engineer, T2C Minerais Industriais, Mogi das Cruzes, SP, Brazil, verbal information, 11<sup>th</sup> March 2018.

## Sulfur

Sulfur occurs in three principal forms: elemental sulfur, sulfate, and sulfide. Sulfur deposits are often associated with volcanic eruptions in volcanic environments, predominantly in convergent plate boundaries and in active volcanic island arc and continental volcanic arc settings. Another source of elemental sulfur is industrial hydrocarbon processing. Sulfate, as gypsum or anhydrite, is primarily found in evaporite sequences, in intraplate environments; gypsum is widely used to correct Al toxicities in soils, as well as to remediate sodic soils. (van Straaten, 2007).

## Calcium and magnesium

The main geological sources of Ca and Mg are sedimentary carbonates, as limestones and dolostones, whereas a source of sedimentary Ca is gypsum (van Straaten, 2007). Limestones occur predominantly in shallow marine environments, generally less than 30–50 m deep, where the water is clean and warm (25–30°C) (Blatt et al., 2006). Therefore, the distribution of modern carbonate sediments is restricted to warm shelf and reef environments in areas with little turbidity, in beach environments at the edges of continents, and surrounding tropical islands (Blatt et al., 2006). This indicates that limestone was formed in large volumes during time periods with warm water regimes, as the Cretaceous, but only in small amounts in periods with glaciations, as the Permo-Carboniferous in former Gondwana (Blatt et al., 2006). Dolostones form primarily through the post-depositional alteration of limestones by Mg-rich waters.

Worldwide, carbonates are the agrominerals most widely used as liming materials to correct soil acidity. Sedimentary carbonates occur in many geological settings, but preferentially in plate margins, formed in shallow and warm waters, whereas metamorphic carbonates, in the form of marbles, are mainly found in mobile belts in stable-shield areas (Blatt et al., 2006). Igneous carbonates are relatively rare, occurring in carbonatites.

Large resources of Mg-rich agrominerals are related to ultramafic rock types, such as serpentinites, and to minerals as phlogopite and vermiculite (van Straaten, 2007). Mg silicates are used in some parts of the world on Mg-deficient soils.



## Micronutrients

Elevated concentrations of micronutrients, such as copper, zinc, iron, manganese, and cobalt, are contained in many basaltic rock types and other mafic igneous rocks (van Straaten, 2007). An interesting compilation of the distribution of boron in relation to plate tectonic settings is presented by Ozol (1978).

### 8. Agromineral resources that improve soil physical and chemical properties

Carbonates, like limestones and dolostones, are the most common agromineral resources used to improve acid soils by raising their pH or reducing Al toxicity in temperate and tropical agriculture (van Straaten, 2007), which could also be achieved by the application of finely ground basalts. Those resources are found in many environments but especially in plate margin settings.

Another important agromineral that reduces Al toxicity and ameliorates sodic soils is gypsum, reported in evaporite basins (van Straaten, 2007).

Zeolites, which are aluminum silicates with high internal surfaces and cation exchange capacities, are used in horticulture and animal husbandry, as well as for environmental applications (van Straaten, 2007). Besides their high cation exchange capacities, those agrominerals have high selectivity for uptake and storage of cations like ammonium ( $\text{NH}_4^+$ ) and  $\text{K}^+$ . Considered “specialty minerals”, zeolites are found concentrated and in economic quantities in: Si-rich volcanic environments, such as volcanic island arc environments; active continental volcanic arc margins; and rift environments, predominantly but not exclusively of Tertiary to Recent age. A wide variety of zeolites are also present as accessory minerals in basalts, such as the flood basalts of the Serra Geral Group in Southern Brazil (verbal information)<sup>2</sup>.

Vermiculites are phyllosilicates with high water-holding and high cation exchange capacities. They are used primarily in horticultural operations and are found in economic quantities in association with carbonatites in extensional intraplate positions (van Straaten, 2007).

Perlites and pumice are highly siliceous volcanic rocks that are used in horticultural operations to increase aeration in soils (van Straaten, 2007). They are found primarily in volcanic areas, specifically in those with extrusive high silica volcanic rocks such as rhyolites and rhyodacites, but also in large quantities in active plate tectonic margins and in rift environments. The age of those resources is Tertiary and younger.

### 9. Potential of finely ground agromineral resources for direct application on soils

The main agrominerals used without chemical modification, only by fine grinding, are sedimentary rocks like carbonates and gypsum, as well as igneous rocks, including basalt, melilite-nephelinite tephra, and K-rich phonolite. While basalt is found in many environments, phonolites, basanites, nephelinites, and silica undersaturated K-rich volcanic rocks are reported predominantly in extensional tectonic environments, as, for example, rifts.

Sedimentary carbonates, the most common liming materials used in the world, occur widespread in coastal zones, plate margins, and shallow water basins (Blatt et al., 2006). Calcium sulfates, known as gypsum, occur in evaporite basins, mainly in intraplate environments, continental rift and marine rift environments, as well as in foreland basins (Blatt et al., 2006; van Straaten, 2007).

Finely ground phosphate rock wastes and other mine rejects found in tailings already have a high potential for direct application, especially on nutrient-depleted acid soils (van Straaten, 2007). However, like all agromineral resources, they need to be tested for their nutrient reserves and potentially detrimental elements for agricultural soils.

Basalt rocks are found worldwide in different geological settings, from convergent to divergent plate boundaries, in intraplate extensional settings and over LIPs, but rarely in passive margin settings. They are reported in Precambrian to Recent rock suites and occur on all continents, being widespread, with no risks of resource exhaustion and with suitable compositions for direct application on highly degraded soils. In support of new farming strategies, agromineral resource wastes, like discarded basalt fines, especially from young, glass-rich basalts, will be transformed from a mineral waste rock to a valuable soil remineralizer.

<sup>2</sup> Ms. Magda Bergmann, Geologa, CPRM, Geol. Survey Brazil, Porto Alegre, RS, Brazil, verbal information during field trip, 25th April 2014.

K-rich phonolite/nepheline syenite complexes, as well as basanites and tephrites, leucite-bearing volcanic rocks and kamafugites, are found mainly in extensional settings, as, for example, in intraplate rift environments, or are associated with extensive deep-seated structural lineaments and structural dome areas. Melilite-nephelinites from the volcanic Eifel mountains in Germany have been used successfully as soil amendments for many decades (Shah et al., 2012).

## 10. Current and future development of agromineral resources

This review paper shows where suitable agromineral resources can be found for use in agriculture. To develop these resources, it is of utmost importance that geologists/mineralogists, soil scientists, and agronomists work together both to characterize and test these resources on a scientific basis, and to assess the potential costs and benefits of their application.

An example of a research on this path is that of Lefebvre et al. (2019), who provided a detailed life cycle analysis of the potential use of basaltic rocks as a greenhouse gas removal technology through soil carbonation and enhanced weathering. The scientists not only studied this, but also environmental costs, including crushing, transportation, and spreading. Furthermore, it must be noted that the application of these finely ground basaltic rock resources not only has the potential to contribute to long-term carbon dioxide sequestration but also has beneficial effects on soil health and productivity through remineralization. Works in Australia, Southeast Asia, and other parts of the world have shown the positive agronomic effects of basalt application on tropical soils (Coventry et al., 2001; Gillman et al., 2002; Anda et al., 2009, 2015). However, it is important to realize that when finely ground basaltic rocks are applied to enhance soil health and crop production, carbon dioxide can be sequestered as well. Further quantitative investigations are needed to assess the potential double benefits of applying finely ground basaltic rocks, i.e., carbon dioxide capture and, at the same time, soil fertility improvement and remineralization.

### Concluding remarks

Agrominerals are not distributed equally across the globe. The conditions for the accumulation of

agromineral resources has changed over the history of Earth, caused primarily by plate tectonics, when the rigid and brittle upper portion of Earth, the lithosphere, glide over the underlying warmer and more plastic portion of the mantle, the asthenosphere. These slow movements of plates, the intermittent breaking up of plates, the convergence and divergence at plate margins, and the rearrangement of the configuration of plates in space and time have major biochemical and physical implications for the surface of the Earth, as well as climatic consequences. These dynamic processes cause not only changes to the distribution of land and sea, but also to climate and oceanography over time, profoundly affecting the formation and distribution of agrominerals.

This paper provides a conceptual framework for agromineral distribution in space and time. As shown, most agrominerals are formed at the active and/or passive edges of continental plates. Examples include sedimentary phosphate rocks, K-silicate sediments (e.g., glauconites), carbonates, as well as volcanogenic sulfur, perlite/pumice, and zeolites. The agromineral resources found in structural zones related to crustal extension and mantle upwelling, such as rifts and fault-bounded zones, include igneous phosphate deposits related to carbonatites, vermiculite, and, in sedimentary basins, K evaporites, gypsum, and carbonates.

Therefore, each agromineral has its specific distribution in space and time. While some of them are concentrated in specific geotectonic settings, others, like carbonates and basalt, are quite common in many geological environments worldwide. These rock types, together with other nutrient-rich volcanic rocks as phonolites and kamafugites, have a high potential to be used as directly applied soil amendments and as soil remineralizers for new and innovative farming strategies.

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