Bulletin of Geosciences, Vol. 79, No. 4, 195–204, 2004

Gravitationally banded ("Uruguay-type") agates in basaltic rocks – where and when?

Jan Petránek

Na Hřebenkách 74, CZ-150 00 Praha

Abstract. The terms *gravitational* and *adhesional* banding of agates, as opposed to *Uruguay, concentric*, *common*, *normal,* and *fortification* banding, are recommended toward alleviating confusion and because they bear clear, easily distinguishable genetic implications. Gravitational banding results from the deposition of coagulated silicic acid by the force of gravity (i.e. like sedimentation), whereas adhesional banding forms by the adhesion of silica to the walls of vesicles. Gravitational banding is distinguishable from adhesional banding by greater band thickness and less distinct boundaries.
Gravitational banding occurs especially in continental flood basalts (plateau basalts). Because of the enormous size of these flows, the increased terrestrial thermal flow was sustained, while the temperature of percolating fluids, mostly of meteoric origin, was raised mostly during the early stages of chemical weathering. The least stable constituents of the basalts are significantly affected by these conditions, and supply much monomeric silicic acid capable of diffusion. Thus, gravitational banding is most often confined to the bottom of agate accumulations.
The main factors that encourage the generation of gravitational banding are: (1) considerable lava thickness and prolonged thermal flow, (2) abundance of mineral constituents that decompose relatively easily, (3) increased carbon dioxide in the atmosphere and in the fluids circulating within the volcanics, (4) warm climate, and (5) sufficient precipitation.
The quantity of rainfall is of considerable importance, as shown by agates in the Permian mafic lavas of the Czech Republic and Germany, and in Triassic flows in Morocco. In the present article, it is suggested that the generation of both gravitational and adhesional banding is largely controlled by climate.

Key words: agates, gravitational banding, adhesional banding, basalts

Introduction

Several types of agates are currently known, among which the most common are those with bands that seem to have circumscribed the walls of the vesicles in which they formed. Another characteristic type, though much less common, typically exhibits *gravitational banding**, i.e. straight parallel banding, often called *Uruguay banding*. Consequently, agates with this banding are termed *Uruguay agates.* This term introduces considerable confusion, as it may only mean the presence of bands of the Uruguay-type, regardless of the agate's geographical origin (e.g., Walger 1954, Harder 1993), whereas other authors understand by this term agates of any type that originate from Uruguay. Synonyms currently in use include *Uruguay-banded agate*; in German *Achat mit Uruguay-Struktur* (Landmesser 1984), and *Lagen-Achat* (Arnoth 1986); and in Russian *onyx-agate* or *parallel zoned agate* (Godovikov et al. 1987). The designation "Uruguay agate" originated from the relatively frequent occurrence of such agates in the Paraná continental flood basalts in Brazil and adjoining parts of Uruguay, Paraguay, and Argentina.

Gravitational banding results from the sedimentation of gelatinous silica particles in parallel layers, mostly at or near the bottom of vesicles. For this reason, the term *gravitational banding* will be used instead of *Uruguay banding* in this paper, as the former term has a clear genetic implication without confusing geographical connotations.

The more common principal type of banding results from the adhesion of gelatinous silica to the walls of a cavity, creating multiple thin bands. There exist various descriptive names for this type of banding, such as *zonally concentric banding, common banding, fortification banding,* and *wall-paper banding*; the agates are called *banded agates*, *fortification agates* or *concentric layer agates* (Harder 1993), or *wall-layered agate type* (Holzhey 2001). In German such terms include *Bandachat*, *Kreisachat, Festungsachat* (Blankenburg 1988), *Bänder-Achat* (Arnoth 1986), and *wandgebänderter Achat* (Holzhey 2003). All these terms, however, lack any general consensus. The present author therefore proposes the term *adhesional banding*, as this term bears a genetic implication and serves as a counterpart to the term *gravitational banding.*

Gravitationally banded agates are most often found in continental flood basalts (CFB), for example in Brazil, India, and Ethiopia. The properties and environmental conditions that favour the generation of gravitationally banded agates will be examined and briefly compared with those of basaltic rocks that are relatively poor in this type of agate.

The enormous thickness and extent of CFBs, and the duration of their extrusion, largely exclude the possibility of petrological and compositional uniformity. The rocks of CFBs are commonly designated as *basalts* or *basaltoids*, which are broad terms that refer to basalts and some andesites, latites, and other rocks with a variety of relations to basalts.

* The term *gravitational* was used by Dymkov (1960) when describing the structure of nasturan (metacolloidal uraninite). Dymkov et al. (1970, p. 217) proposed the general use of the term *gravitational* for all structures (textures) caused by the force of gravity. This term was used for agates by Zhabin (1974).

Banding formed by the force of gravity

Gravitational banding results from the settling of coagulated colloidal particles of silicic acid [$Si(OH)_4$] by the force of gravity. This banding is mostly confined to the lower parts of agates (Figs 1, 2, 7). As true sediments, these bands originally occupy a horizontal position, and are thus an indication of the initial orientation of the vesicle in the parent volcanic rock. Some agates, mostly of smaller size, are comprised entirely of gravitational bands (Fig. 4).

Gravitational bands usually differ from adhesional bands by their considerably greater thickness (Figs 4, 6a, b), lesser regularity, and often indistinct boundaries with each other. Furthermore, a change of colour may be observed within a single band (Figs 4, 6a) and the coherence of the bands tends to be decreased (some break apart along their bedding planes). There also exist restricted transitional periods characterized by the alternation of gravitational and adhesional banding (Fig. 5), and in some cases thick gravitational bands continue as thin adhesional bands circumscribing the cavity in which they formed. The conditions enabling the deposition of gravitational bands may sometimes end and recur (Fig. 5).

Figure1. Brazilian agate with typical gravitational banding in its lower part, followed by adhesionally banded microcrystalline quartz. The adhesional bands overlying the gravitational bands are parallel with their “substratum” and are typically of a constant thickness when circumscribing and lining the walls of the vesicles in which they formed. Macroquartz crystallized from the last diluted and uncontaminated solutions, and because of insufficient supply a cavity was left. Size 8 × 13 cm.

Later adhesional bands coat the irregularly shaped cavity, though their bottom-most extent naturally forms parallel to the preceding horizontal gravitational banding. The two types can thus resemble each other, though adhesional bands are distinguished by the clear continuity of their fine and regular banding (Fig.1).

Occurrences of gravitationally banded agates

Gravitationally banded agates are most frequently found in CFBs, but are uncommon or absent from other types of basaltic effusions. CFBs are mostly of tholeitic composition, and are usually associated with large fissure eruptions. These lavas result either from hotspots or upwelling mantle plumes, with or without an upper mantle contribution. Because of their deep origins, the temperature of such lavas are notably higher, resulting in lower viscosity lava flows that are able to cover extensive areas. Vesicles form in gas-rich lavas in low pressure environments. The cooling of such lava flows would be retarded because of their considerable thickness, allowing gas bubbles to coalesce on their way up, forming larger vesicles of subspherical or elongated forms.

The most important CFB occurrences, in order of decreasing geological age, are as follows: Emeishan, Siberian Traps, Karoo-Ferrar-Tasmania, Paraná and Etendeka, Madagascar, Deccan Traps, Ethiopia and Yemen, and Columbia River (Farmer 2004, Luhr 2003).

The Emeishan flood basalts are situated in southwestern China. They erupted around 259 million years ago, near the end of the Permian period when the most devastating extinction event in Earth’s history occurred (about 90% of organism genera were eliminated).

The Siberian traps (248 Ma) erupted in northern Siberia near the beginning of the Triassic period. This volcanic activity was preceded by the collision of Siberia with Baltica (about 270–260 Ma) which led to the building of the Ural Mts. and apparently lessened the coherence of Siberia (such that fractured crust promoted the outpouring of lavas). The Siberian traps are the most extensive of all known flood basalts, covering an area of about 2 million square km (Farmer 2004).

The Karoo (Lesotho) – Ferrar (Antarctica) – Tasmania flood basalts are of the Early Jurassic age (183 Ma). These eruptions took place at the time when the break-up of Pangea was under way, though South Africa was not yet separated from Antarctica and Tasmania.

The Paraná and Etendeka flood basalts erupted about 132 million years ago (the Early Cretaceous). This volcanic activity coincided with the separation of South America from Africa and the opening of the south Atlantic Ocean. The heat from the mantle formed the Walvis hotspot under the Paraná region of eastern South America and present-day Namibia in southwest Africa, which at that time were not yet separated. Doming of the crust over a 1,000 km wide zone caused the development of deep, extensive fractures through which lava poured onto the surface. In the Paraná area basalts cover about 1 million square km and their present maximum thickness is up to 1,800 m (Beurlen 1970).

The Late Cretaceous Madagascar flood basalts (88 Ma) are of smaller extent and are situated in the southern part of that island.

The Deccan traps (basalts) erupted about 66 million years ago, close to the Cretaceous/Tertiary boundary. The eruptions occurred during the northward movement of the Indian plate, which later led to collision with the Eurasian plate (resulting in building up the Himalayan Mountains).

The Oligocene Ethiopian and Yemeni volcanics are 31–26 Ma old. They were originally joined, but later became separated by the development of the Red Sea rift. The Ethiopian part of the volcanic plateau is situated in a tectonically exposed position, close to the East African rift system. These volcanics are at least 2,000 m thick; their eruption was discontinuous but of long duration (based on intercalations of fluvial and lacustrine sediments).

The CFBs of the Columbia River Plateau occur in the northwestern part of the USA, in the states of Washington, Oregon, and Idaho. They are the youngest (about Middle Miocene, ~16 Ma) and the smallest (approximately 200,000 square km) of all known flood basalts.

In general, the CFBs are causally linked to tectonic movements or with the doming (extension) of the lithosphere resulting in localized continental rifting, as for example in East Africa.

Figure 2. A thick sequence of parallel bands. Not all are of gravitational origin, since a few of them continue in a thinned form as adhesional bands circumscribing the void in which they formed. The typical adhesional banding formed during the final phase. Origin: southern Brazil or Uruguay. Size 7 × 8 cm.

Chemical composition of flood basalts

The chemical weathering of rocks largely depends on their chemical composition and the stability of their minerals. The contents of MgO, CaO, and alkalis (Na_2O, K_2O) in leachates are especially important, since these constituents contribute significantly to the alkalizing of circulating fluids and promote the dissolution and diffusion of silica in the form of ionized silicic acid [$Si(OH)_4$].

The average contents of SiO_2, MgO, CaO, Na_2O, and K_2O (wt.%) in continental basalts and continental tholeiitic basalts after Manson (1967) and in continental flood basalts as selected by Farmer (2004), are presented in Table 1.

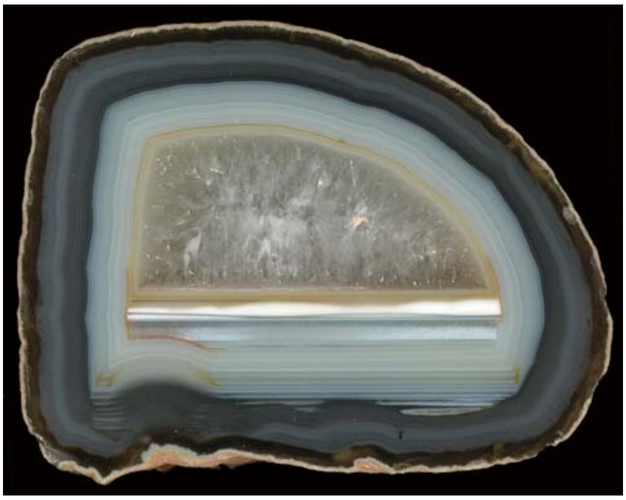

Figure 3. Brazilian agate with a relatively thick chalcedony rind, followed by thin gravitational bands that were superseded by typical adhesional bands. The latter subsequently gave way to a few gravitational bands (partly of white colour), followed again by thin adhesional banding (light brown), and finally macrocrystalline quartz. Size 9 × 6.5 cm.

Table 1. Average contents of selected oxides (wt.%) in some basaltic rocks (Manson 1967, Farmer 2004)

	Continental		Columbia River	Deccan	Siberian	Brazilian flood basalts		
	basalts	tholeiitic basalts	basalts	traps	traps	Esmeralda	Gramado	Urubici
Number of analyses	1513	946	16	24	16	1	1	1
SiO_2	49.9	51.5	54.7	48.7–49.5	48.5–51.8	51.1	50.9	53.0
MgO	6.3	5.9	4.20	5.7–6.9	6.8–13.0	6.1	8.0	4.3
CaO	9.8	9.8	7.99	10.28–10.45	8.65–10.45	10.73	11.61	8.30
Na_2O	2.8	2.5	3.06	2.51	2.12–2.37	2.55	2.44	2.57
K_2O	1.1	0.86	1.44	0.34–0.40	0.38–1.35	0.54	0.51	1.70

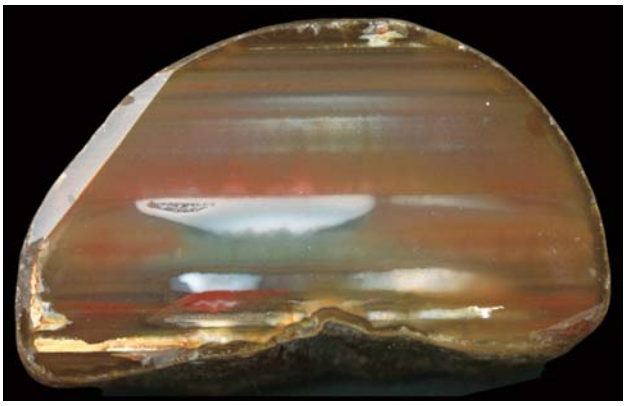

Figure 4. Brazilian gravitationally-banded agate. The bands show diffuse boundaries with each other and changing colours. Size 3.5 × 6.5 cm.

Figure 5. Brazilian agate of complex structure, consisting successively of (a) adhesional chalcedony rind, (b) indistinct gravitational bands, (c) adhesional bands interlaminated with a few brownish gravitational bands, (d) macroquartz, (e) adhesional whitish chalcedony, (d) final filling of the void by gravitational bands. This is a fine example of the greatly fluctuating nature of the solutions. Size 7.5 × 9 cm.

In contrast to the somewhat unusual Columbia River flood basalts, some of the other flood basalts show a slightly increased CaO content and fluctuating amounts of K_2O when compared with average tholeiitic basalts; otherwise, there are generally no marked discrepancies.

Climate

Climatic conditions, especially temperature and precipitation, are important factors in determining the intensity and rate of chemical and physical weathering. In the process of chemical weathering the breaking down of the less stable mafic and felsic minerals would be slowed by a lack of precipitation, such as in subarid or arid environments. Temperature is also of considerable importance, as heat enhances the dissolving capability of the penetrating fluids.

A major problem in evaluating the role of climate in the generation of agates in particular volcanic areas is that the time during which gravitational and adhesive agates are generated may differ considerably from that of the eruption of the lava rocks in which they form. For example, when lavas erupt in an arid and cool environment, it could happen that intense chemical weathering starts only after a considerable delay (in terms of geological time) when the climatic conditions became more favourable.

Various uncertainties exist concerning climates during the early Phanerozoic, though data on Mesozoic and Cenozoic climates and atmospheric conditions are becoming increasingly available. We will now consider the data on the climatic conditions under which the CFBs were extruded.

The eruption of the Emeishan plateau-basalts (259 Ma) and the Siberian traps (248 Ma) took place close to the Permian/Triassic boundary (252 Ma). Though wet seasons also occurred in the Permian and Triassic, both periods were generally characterized by aridity, warm climates, and rising CO_2 contents in the atmosphere. The mid-Triassic climate was possibly the most arid in all of Earth history (Frakes 1979), during which temperatures at 60° paleolatitude did not greatly differ from those in equatorial zones.

The Karoo-Ferrar-Tasmania flood basalts (183 Ma) extruded close to the Early/Middle Jurassic (Lias/Dogger) boundary (180 Ma). The Jurassic climate as a whole is still considered to be arid, but the early third of the period seems to have been cooler and more humid. Temperatures subsequently began to rise, especially towards the end of the Jurassic.

The Paraná and Etendeka flood-basalts (132 Ma) stratigraphically correspond to the middle part of the Lower Cretaceous, and their eruptions occurred at approximately 45° paleolatitude. The then warm climate (which may have been 10 °C higher than the present annual temperature) was relatively dry globally, though seasonal wet periods and increased atmospheric CO_2 favoured intense chemical weathering. The tropical to subtropical conditions (of the modern type) extended during the warmest period to 70 °S paleolatitude because of the ocean current patterns (Frakes 1979).

The Madagascar plateau basalts (88 Ma, Upper Cretaceous) extruded in a warm climate and in an atmosphere significantly enriched in carbon dioxide.

The Deccan traps (66 Ma) erupted very close to the Cretaceous/Tertiary boundary (65 Ma). The atmosphere was still enriched in carbon dioxide, but the Late Cretaceous temperature was decreasing and changed markedly during the end of that period. During the Late Cretaceous there was a global increase of humidity.

The decrease in annual temperature that started in the Cretaceous continued into the Paleogene. Temperatures declined from the beginning of the Paleocene until the end of the Eocene or Middle Oligocene. This decrease slowed before increasing greatly by the Middle Miocene. The Ethiopian and Yemeni flood basalts (31–26 Ma) are of Oligocene age (33.5–24 Ma) and were extruded during a period of rapid cooling. The decrease in precipitation, notable in high latitudes, did not markedly affect the zone in which these eruptions occurred.

The Columbia River basalts (16 Ma) are approximately of Middle Miocene age. This period is characterized by pronounced cooling, contrary to the warmer climates of both the preceding period and the ensuing Late Miocene; the climates, however, were wetter than at present (Frakes 1979).

Atmosphere

The composition of the atmosphere has fluctuated throughout Earth's history, principally concerning oxygen and carbon dioxide (CO_2) contents. Carbon dioxide is produced by micro-organisms in the soil and reacts with the permeating meteoric waters, though rainfall already becomes significantly enriched in dissolved CO_2 in the atmosphere. The carbon dioxide dissolves in water to form carbonic acid, a highly effective agent of chemical weathering. In certain periods of the geological past, the atmosphere was richer in CO_2 and this could have resulted in the faster and more intensive chemical weathering of basalts, i.e. in speeding-up the production of larger quantities of silicic acid. This would favour the generation of gravitationally-banded agates.

Some data on the atmospheric content of CO_2 in the geological past follows (Luhr 2003):

260 Ma: rising CO_2 content	
	259 Ma: Emeishan flood basalts
	248 Ma: Siberian traps
240 Ma: CO_2 at 5x present level	
	183 Ma: Karoo-Ferrar-Tasmania flood basalts
180 Ma: CO_2 at 3.5x present level	
150 Ma: CO_2 at 3.5x present level	
	132 Ma: Paraná and Etendeka flood basalts
120 Ma: CO_2 at 4x present level	
	88 Ma: Madagascar flood basalts
70 Ma: CO_2 at 2x present level	
	66 Ma: Deccan traps
50 Ma: CO_2 at 2x present level	
	31–26 Ma: Ethiopia and Yemeni traps
	16 Ma: Columbia River flood basalts

The ages of some CFBs and the corresponding atmospheric CO_2 contents suggest that the degassing associated with the eruption of flood basalts could have notably contributed to the increase of atmospheric CO_2. According to Shepherd (1938), gas escaping from lava of the Kilauea volcano in Hawaii contained an average of 24.22% CO_2 (average of 6 analyses), while the fumarole gases of Showa-shinzan volcano in northern Japan contained on the H_2O-free basis 74.57% CO_2 (White and Waring, 1963). According to Lange (1994) the pre-eruptive contents of volatiles in magmas were much higher than generally assumed (CO_2 + H_2O of at least 4 wt.%) and thus the flood basalts and their post-erpution emanations could have greatly contributed to the increase of CO_2 in the atmosphere.

Weathering

The cooling and contraction of basalts causes them to fracture and disintegrate, making them susceptible to physical and chemical weathering. There are several agents of chemical weathering, and their activity is often combined. The process of the chemical leaching may involve juvenile waters capable of removing various mineral constituents from basalts and forming secondary minerals. The temperatures of juvenile waters must be less than 300 °C in order to deposit silica in the form of chalcedony, and it is certain that juvenile waters were unable to supply enough silica to account for the substantial amounts of agates that occur in CFBs. Much more likely is the mixing of ascending hydrothermal fluids with descending meteoric waters, during which the descending meteoric waters became heated and were thus turned into hydrothermal fluids. Even normal chemical weathering, involving only meteoric waters, given sufficient time and favourable conditions (especially climatic factors such as atmosphere, temperature, humidity), would be similarly effective. For example Gilg et al. (2003) ascribe the origin of south Brazilian amethyst geodes (with some agate) to solutions of meteoric origin.

Several authors therefore relate the generation of agates to conditions of low temperature and pressure, i.e. to sedimentary-diagenetic conditions (see Landmesser 1984, 1992 Harder 1993) with temperatures not surpassing 150 °C. According to Götze et al. (2001a) the study of trace elements and stable isotopes in agates from various volcanics and occurrences indicates a temperature range of ca. 50 to 250 °C or 50–200 °C (Götze et al. 2001b). According to Gilg et al. (2003) the study of isotopes and fluid inclusions in the south Brazilian amethyst geodes (with agate rims) indicate a temperature of origin of less than 100 °C. Agates in the Early Carboniferous sediments of Kentucky and Tennessee (eastern USA) seem to have originated at temperatures less than 40 °C (Milliken1979).

Chemical weathering of any kind variously affects different minerals. Metastable volcanic glasses that occur abundantly in hypocrystalline basalts and their pyroclastics have the greatest weathering potential (the same applies to acid volcanics such as rhyolites; see Holzhey 2001). The weathering rates of minerals in igneous rocks, established separately for mafic and felsic minerals and in order of increasing stability (Krauskopf 1967), are as follows:

Mafic minerals: olivine – pyroxene – amphibole – biotite.

Felsic minerals: Ca-Na plagioclase – Na-Ca plagioclase – K feldspar – muscovite – quartz.

Clinopyroxene is an abundant constituent of tholeiitic basalts, whereas olivine is less common. Ca-Na plagioclase (labradorite) is the principal feldspar. These minerals undergo hydrolytical decomposition in a process of chemical weathering that produces ions of silicic acid, iron, aluminum, as well as of alkaline and alkaline-earths elements. The chemical decay of basalts is aided by carbon dioxide dissolved in water (carbonic acid), but even more so by decaying humus in the soil, which may decrease the pH

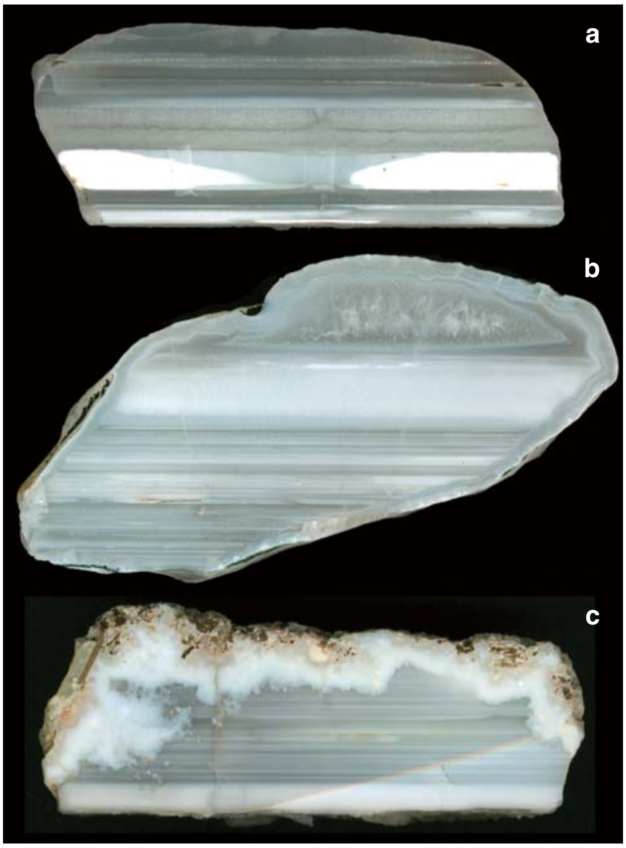

Figure 6. Ethiopian gravitationally banded agates. a – Bands show marked differences in colouring; the lower part of the agate nodule is broken-away; southwest of Bahir Dar, 7 × 2.5 cm. b – Gravitational bands are superseded by a few adhesional bands, with macroquartz filling the remaining void; southwest of Bahir Dar, 7.5 × 3.5 cm. c – Incomplete gravitationally banded agate, originally with a ?mordenite rim later replaced by silica; south of Dire Dawa, 6.5 × 2.5 cm.

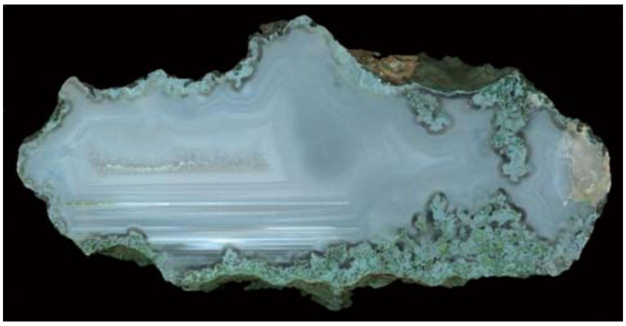

Figure 7. The seladonite-bearing rind encloses only a few thin gravitational bands, and the ensuing adhesional bands are parallel to the underlying gravitational bands; Ethiopia, south of Dese, 4.5 × 10 cm.

to 4.5 or less, and thus make the leaching of the rocks especially effective.

Solutions transporting leached and dissolved silica need not be only descending. In warm environments, where humid and dry periods alternate and where lateritic soils form during the dry periods, the solutions rise upwards due to evaporation. All of these processes lead to the concentration of solutions. The pH of these solutions results in an increased solubility and mobility of silica, and thus enhances the possibility of silica deposition in volcanic vesicles.

Silica

Chemical weathering produces monomeric silicic acid. In this ionized form silica is capable of being spread by diffusion (Landmesser 1988) and entering into vesicles (contrary to its polymeric colloidal form). The fluids must become alkaline in a later phase, since the chemical leaching affects minerals rich in magnesium, calcium, and also some sodium and small amounts of potassium. The ions of these alkaline and alkaline-earth elements increase the pH of circulating fluids, and thus increase the mobility of silica.

In the course of time and upon an increase in concentration, the silicic acid that diffuses into the vesicles slowly turns into a sol. The later coagulation of sols may result from any of the following: (a) increase in the sizes of polymerized particles, (b) the long standing of the sol, (c) the cooling of the sol (parallel with the continuing cooling of the volcanics), (d) decrease in pH, or (e) electrolytes acting as coagulants. As the colloidal particles of silica bear a negative charge, they coagulate when encountering positively charged divalent or trivalent ions, whereas univalent ions are less effective in this respect (Krauskopf 1967). The most important coagulants are probably Mg^{++} and Ca^{++} ions, since Al^{3+} and Fe^{3+} tend to bind in clay minerals and also concentrate at or close to the Earth's surface, especially in the course of lateritic weathering. Due to the force of gravity, the coagulated particles of silica settle out of the solution as horizontal layers of gelatinous precipitates.

That the temperatures in which the silica is deposited could have been rather low, even in volcanic rocks, is evidenced by typical agates that formed in sedimentary rocks, such as occurs in silicified wood, corals, saurian bones, molluscan exoskeletons, and voids left after the dissolution of earlier anhydrite concretions.

Regardless of when the coagulation of the silicic acid takes place, the chemical equilibrium between the solutions inside and outside the vesicles becomes imbalanced, causing the diffusion of siliceous ions into the agate void from outside to accelerate in order to renew the chemical equilibrium. This occurs especially when gelatinous silica forms bands circumscribing the walls of vesicles. For experiments pertaining to the final processes leading from colloidal silicic acid to the crystallization of quartz, see Harder and Flehmig (1970).

Volcanic rocks in which gravitationally banded agates are rare or absent

In the interest of comparing the conditions that favour the generation of gravitational banding with those that do not, the origin of agates in the Krkonoše-Piedmont Basin (Bohemia, Czech Republic) will be discussed. Agates occur in the partly altered basalt-andesites, traditionally called melaphyres (Gotthard 1933, Schovánková 1989). These volcanics are of the Early Permian age (Asselian–Sakmaran, 290–269 Ma) and are interbedded with redbeds (Prouza and Tásler 2001). The agates, though rather varied in their internal structure, are not gravitationally banded.

One flow in this volcanic complex attained a thickness of more than 160 m (the Kozákov flow), though the others are only a few tens of metres thick. Because of this thinness and the consequent relatively rapid cooling and solidifying of these flows, large gas-filled cavities formed only rarely. The agates they contain are small, averaging 3–5 cm in diameter, in contrast to those found in CFBs.

The Permian climate was warm, and the site of the eruption was situated at about 15° N paleolatitude at that time (estimate based on paleogeographical global map by Drewry et al. 1974). The Permian sequence is of a continental nature, and must have originated in an arid climate as it includes redbeds and feldspathic clastics (mainly arkoses). It is suggested that the arid climate largely prevented the generation of gravitationally banded agates, as limited rainfall greatly restricted chemical weathering and the consequent formation of new minerals. The following Triassic period was warm and even more arid (Frakes 1979, Robinson 1973), during which the paleolatitude of Central Europe was about 30° N (Drewry et al. 1974). Such a climate is reflected in the greatly curtailed deposition of sediments in the Bohemian Massif. The Jurassic period was still rather warm, though a gradual amelioration of climate took place. Intensive weathering processes, with some lateritization and increased silica solubility, were active mainly during the Lower Cretaceous. It is suggested that the generation of agates in the northeastern Bohemia must have concluded at some time preceding the Late Cretaceous (Cenomanian) transgression. Paleocene and Eocene climates (both temperature and rainfall) were also favourable to the formation of agates, but at that time the volcanics were still covered by thick Late Cretaceous sediments.

The Permian of the Krkonoše-Piedmont Basin is similar in several aspects to the Permian of the Saar-Nahe region (southwestern Germany). That region contains agate-bearing basaltic rocks of the latiandesite and latibasalt types (Bambauer 1970, Laarmann 2000), especially in the renowned area of Idar-Oberstein. In both regions the volcanism is of subsequent type and of the Early Permian age. At that time, both areas were situated at approximately 15° N latitude, and their climate was arid. The gravitationally-banded agates in the Saar-Nahe region are rare – e. g., Walger (1954) reported their occurrence in Flohnheim (Rheinhessen); two small, gravitationally banded agates are illustrated by Henkel (2000) and Landmesser (2000); and a fragment of a large gravitationally banded agate was found by H. Schumann (personal communication) in Hahnweiler near Freisen in northern Saarland. One locality in northwestern Saxony (Gröppendorf) also yielded some gravitationally banded agates (Seifert and Riedrich 1993). The paucity of gravitationally banded agates in the German Permian is no doubt related to the same causes as in Bohemia.

Similarly, the extensive basaltic flows of southern Morocco, which are so rich in agates, lack gravitationally banded agates (though some rare occurrence cannot be excluded). These basalts are of the Triassic age, which is considered by some to have been the driest period in Earth history (Frakes 1979).

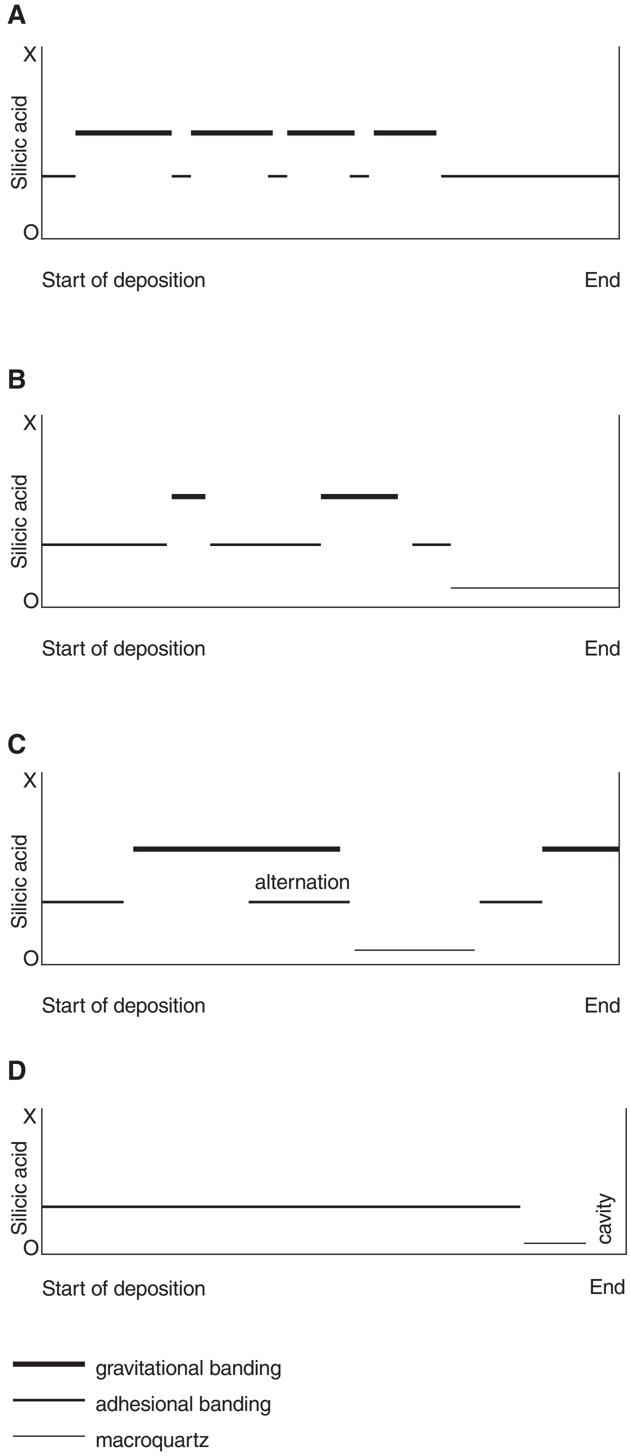

Figure 8. Schematic presentation of the succession of gravitational and adhesional bands, and macroquartz in agates: A – corresponds to Fig. 2; B – corresponds to Fig. 3; C – corresponds to Fig. 5; D – is an idealized succession of quartz types in some agates from lavas that were extruded in a warm and arid environment.

The chemical weathering of volcanics in arid or subarid environments, though long-lasting, seems unable to supply solutions of silicic acid in adequate concentrations and/or quantities for making possible the large scale coagulation of sols coupled with the gravitational settling of colloidal particles, i.e. the generation of gravitationally banded agates. It is suggested that restricted precipitation caused the generation of very fine adhesional banding that contrasts with the thicker gravitational banding so common in agates from continental flood basalts.

It is therefore concluded that the occurrence of gravitational banding and the thickness of individual adhesional bands in agates are climatically controlled to a notable degree.

Dating the generation of agates

When considering the time span during which gravitationally banded and other agates form, the environmental conditions and climatic situation should be carefully evaluated. Juvenile waters could not be prolific enough to supply sufficient quantities of silica in agate-rich volcanics, and there are also temperature limits for chalcedony generation. Meteoric waters are most important when (a) descending to a depth where they become heated, and subsequently leach igneous rocks as hydrothermal fluids, (b) mixing with juvenile waters, or (c) they can act alone as effective solvents during chemical weathering under favourable climatic conditions.

In humid tropical and subtropical climates chemical weathering starts immediately after the eruption of lavas. Conversely, in arid regions or in situations where the lava rocks quickly become covered by thick sequences of other rocks, agates may form only after the climate changes or the rocks are stripped of the overburden that prevents more intense chemical weathering. Therefore, the time interval between the basaltic flow and the generation of agates may be short or very long. It cannot be generalized, but only estimated after careful consideration of various aspects of the environmental conditions and the post-eruption history.

Conclusions

- It is suggested that the term *gravitational* banding be adopted in place of *Uruguay* banding; and that the term *adhesional* banding be adopted in place of *common, zonally concentric*, *fortification* and other designations of banding. Both terms bear an easily recognizable genetic implication, and lack any confusing geographic connotations.
- The gravitational bands usually differ from adhesional ones by their considerably greater thickness, lesser regularity, and sometimes unclear contacts between layers. They tend to occur in the lower parts of agates. They form when coagulated colloidal particles of silica settle under the influence of gravity. Their bands thus form like sediments occupying an originally horizontal position, and are therefore indicative of the initial orientation of the gas cavity in the parent volcanic rock. Some agates, usually of smaller size, may be comprised entirely of gravitational bands.
- Gravitationally-banded agates are usually more abundant in CFBs than in other basaltoid effusions, in which they may even be completely absent. Because of the deep-seated origin of CFBs, the temperature of their lavas was higher than other basalt lavas. This, along with the thickness of CFBs, caused their solidification to be slow; giving gas bubbles time to unite and form larger voids. These conditions also allowed the fluids percolating through basalts to be more effective solvents because of the increased and prolonged thermal flow.
- CFBs are mostly tholeiitic basalts. Their chemical compositions do not substantially differ from those of other continental tholeiitic basalts. The only minor deviation seems to be the somewhat increased content of CaO in some CFBs.
- Gravitational banding mostly forms in the relatively early phase of agate generation. At this stage, the chemical weathering and decomposition of the unstable glasses of hypocrystalline basaltic rocks and the less stable minerals (such as olivine and Ca-Na plagioclase), supply major quantities of silicic acid. The increased temperature of percolating fluids at that time contributed also to the effectiveness of chemical weathering. This is clearly reflected in the preferential localization of gravitational bands in the lower parts of agate nodules.
- During later phases of chemical weathering the more resistant minerals (such as clinopyroxenes, amphiboles and Na-Ca plagioclase, and alkali feldspars) become affected. As the rates by which these minerals were altered and the consequent supply of monomeric silicic acid decreases, the conditions for generating gravitational banding become much less favourable. At this stage, the lining of vesicle walls by the adhesion of gelatinous silica becomes prevalent. During the generation of adhesional banding, however, conditions propitious for the formation of gravitational banding can occasionally recur, causing some gravitational bands to appear interstratified with the prevailing adhesional bands.
- Chemical weathering is most effective in subtropical or tropical regions with sufficient rainfall. Such conditions promote the generation of gravitational banding in agates. On the other hand, arid and/or cool climates retard chemical weathering. The silica leached under these conditions may possibly be sufficient for the generation of adhesionally banded agates, but not for notable quantities of gravitationally banded agates.
- In the geological past, the atmosphere was often greatly enriched in CO_2 (up to 5× present), which markedly raised the aggressiveness of descending meteoric waters percolating through weathering basalts. The degassing of enormous basaltic lava flows also contributed to the increase of atmospheric CO_2.
- Silica leached from basaltic rocks becomes ionized silicic acid, the ions of which spread by diffusion and can enter vesicles. There, after further concentration and upon

standing, the solution slowly turns into a sol that subsequently coagulates. Several factors exist which, individually or in combination, could cause the coagulation process, namely (a) the growth of colloidal particles, (b) the long standing of the sol, (c) the cooling of the sol, or (d) interaction with electrolytes. Since the colloidal silica particles bear a negative charge, positively charged ions of magnesium, calcium, iron, and aluminum could have been very effective coagulants. By the force of gravity, the gelatinous precipitate settled in horizontal, parallel layers.

• The conditions of agate generation in the Early Permian basalt-andesites of the Krkonoše-Piedmont Basin (Czech Republic) are presented for comparison. During the Permian, this region lay approximately at 15° N paleolatitude. The lava flows were thinner than those of flood basalts. The warm and arid Permian climatic conditions continued throughout the Triassic period. In the Jurassic period, the climate started to change gradually, though it seems not to have remained unfavourable for intense chemical weathering. As a result, the generation of agates most probably became a long, slow process that ended prior to the Late Cretaceous (Cenomanian) transgression. Gravitationally banded agates are so far not known in the Krkonoše-Piedmont Basin.

• During the Early Permian, the basaltic rocks of the Saar-Nahe region (southwestern Germany) were extruded and began weathering under similar climatic and geological conditions as those in Bohemia. Gravitationally banded agates are rare or absent in some regions.

• Though the Triassic basaltic flows of southern Morocco are unusually rich in agates, samples showing gravitational banding have not been identified so far (the Triassic period was also extremely arid).

• The chemical weathering of volcanics in arid or subarid environments, though long-lasting, seems mostly unable to supply solutions of silicic acid in adequate concentrations and/or quantities to allow the coagulation of sols coupled with the gravitational settling of coagulated colloidal particles, i.e. the generation of gravitationally banded agates. It is suggested that the restructured precipitations also cause the generation of the very fine adhesional banding that contrasts with the thicker adhesional bands so common in agates from the continental flood basalts. It is assumed that the origin of gravitational and adhesional banding is climatically controlled to a notable degree.

• The time interval between the basaltic effusion and the generation of agates cannot be generalized. In humid tropics and subtropics, intense chemical weathering of basalts started immediately after eruption. On the contrary, in arid or cool regions or when the basaltic lavas quickly became covered by thick sequences of rocks, the chemical weathering was impeded and only became effective following a change in climate and the erosional denudation of the overlying sediments. In unfavourable conditions, the generation of agates is a slow process, and the time span between the eruption of the lavas and the generation of agates could have been considerable.

Acknowledgements. I sincerely thank H. Schumann (Schallenburg, Germany) and Vladimír Prouza (Prague) for their valuable information and steady interest in my work.

References

Arnoth J. (1986): Achate – Bilder im Stein. Buchverlag Basler Zeitung, Basel.

Bambauer H. U. (1970): Der permische Vulkanismus in der Nahe Mulde. Neues Jahrb. Mineral.-Abh. 95, 141–199.

Beurlen K. (1970): Geologie von Brasilien. Beitr. regional. Geol. 9, Borntraeger, Berlin.

Blankenburg H.-J. (1988): Achat. Dt.Verlag f. Grundstoffindustrie, Leipzig.

Drewry G. E., Ramsay A. T. S., Smith A. G. (1974): Climatically controlled sediments, the geomagnetic field, and trade wind belts in Phanerozoic time. J. Geol. 82, 531–553.

Dymkov Yu. M. (1960): Priznaki kristallizacionnogo rosta vydelenii nasturana (Features of the crystallization growth of nasturan). Zap. Vsesoyuz. miner. Obšč. 89, vyp. 6, Moscow. (in Russian)

Dymkov Yu. M., Kazantsev V. V. and Lyubchenko V. A. (1970): Krustifikacionnyye karbonatnyye zhily uran-arsenidnogo mestorozhdeniya (Encrustation carbonate veins of an uranium-arsenic deposit). Sbornik: Mestorozhdeniya urana. Zonalnost i paragenezisy. Atomizdat. (in Russian)

Farmer G. L. (2004): Continental basaltic rocks. In: Holland H. D., Turekian K. K. (eds) Treatise on geochemistry 3, 85–121.

Frakes L. A. (1979): Climates throughout geologic time. Elsevier, Amsterdam.

Gilg H. A., Morteani G., Kostitsyn Yu., Preinfalk Ch., Gatter I., Strieder A. J. (2003): Genesis of amethyst geodes in basaltic rocks of the Serra Geral Formation (Ametista do Sul, Rio Grande do Sul, Brazil): a fluid inclusion, REE, oxygen, carbon, and isotope study on basalt, quartz, and calcite. Miner. Depos. 38, 8, 1009–1025.

Godovikov A. A., Ripinen O. I., Motorin S. G. (1987): Agaty (Agates). Nedra, Moscow. (in Russian)

Gotthard J. (1933): Petrografická povaha melafýrů podkrkonošských. Arch. přírodověd. Prozk. Čech, 18, 2, 1–65. (in Czech)

Götze J., Plotze M., Tichomirowa M., Fuchs H., Pilot J. (2001a): Aluminium in quartz as an indicator of the temperature of formation of agate. Mineral. Mag. 65, 407–413.

Götze J., Tichomirowa M., Fuchs H., Pilot J., Sharp Z. D. (2001b): Geochemistry of agates: a trace element and stable isotope study. Chem. Geol. 175, 523–541.

Harder H. (1993): Agates-formation as a multi component colloidal chemical precipitation at low temperatures. Neu. Jb. Mineral., Mh. 1, 31–48.

Harder H., Flehmig W. (1970): Quarzsynthesen bei tiefen Temperaturen. Geochim. Cosmochim. Acta 34, 295–305.

Henkel M. (2000): "Fundort Idar-Oberstein". Achat, extraLapis 19, 38–47.

Holzhey G. (2001): Contribution to petrochemical-mineralogical characterization of alteration processes within the marginal facies of rhyolitic volcanics of Lower Permian age, Thuringian Forest, Germany. Chem. d. Erde, Geochem. 61, 149–186.

Holzhey G. (2003): Mikrokristalline SiO_2 – Mineralisationen in rhyolithischen Rotliegendvulkaniten des Thüringer Waldes und ihre Genese. Aufschluss 54, 95–110.

Krauskopf K. B. (1967): Introduction to geochemistry. McGraw-Hill, New York.

Laarmann U. (2000): Das Geschenk der permischen Vulkane. Achat, extraLapis 19, 20–29.

Landmesser M. (1984): Das Problem der Achatgenese. Mitt. Ver. Heimatkunde Landkr. Birkenfeld, Sonderh. 49, Birkenfeld.

Landmesser M. (1988): Transport- und Akkumulationsmechanismen des SiO_2 in petrologischen Systemen: Achate. Z. Dt. Gemmol. Ges. 36, 101–119.

Landmesser M. (1992): Zur Geothermometrie und Theorie der Achate. Mitt. Pollichia 79, 159–201.

Landmesser M. (2000): Wie entstehen Achate? Achat, extraLapis 19, 58–73.

Lange R. A. (1994): The effect of H_2O, CO_2, and F on the density and viscosity of silicate melts. Rev. Mineral. 30, 331–369.

Luhr J. F., ed. (2003): Earth. Dorling Kindersley, London.

Manson V. (1967): Geochemistry of basaltic rocks: major elements. In: Hess H. H., Poldervaart A. (eds) Basalts 1, 215–269. Wiley, New York.

Milliken K. L. (1979): The silicified evaporite syndrome. – Two aspects of silicification history of former evaporite nodules from southern Kentucky and northern Tennessee. J. Sed. Petrology 49, 245–256.

Prouza V., Tásler R. (2001): Podkrkonošská pánev. In: Pešek J. (ed.) Geologie a ložiska svrchnopaleozoických limnických pánví České republiky. Český geol. ústav, Praha, 128–166. (in Czech)

Robinson P. L. (1973): Palaeoclimatology and continental drift. In: Tarling D. H. and Runcorn S. K. (eds): Implications of continental drift to the earth sciences. Academic Press, London, 451–476.

Seifert T., Riedrich G. (1993): Die Achate im Melaphyr von Gröppendorf bei Hubertusburg in Sachsen. Mineralien-Welt 1993, 15–16.

Shepherd E. S. (1938): Gases in rocks and some related problems. Am. J. Sci. 235, 311–351.

Schovánková D. (1989): Petrologie mladopaleozoických vulkanitů podkrkonošské pánve – Část 5. Permské bazaltandezity. Report, Archiv Čes. geol. služba, Praha. (in Czech)

Walger E. (1954): Das Vorkommen von Uruguay-Achaten bei Flohnheim in Rheinhessen, seine tektonische Auswertung und seine Bedeutung für die Frage nach der Achatbildung. Jber. Mitt. Oberrhein. geol. Ver., N. F. 36, 20–31.

White D. E., Waring G. A. (1963): Volcanic emanations. Data of geochemistry, U. S. Geol. Survey Prof. Paper, 440-K.

Zhabin A. G. (1974): Gravitacionnyye tekstury agatov v kolchedannych mestorozhdeniyakh (Gravitational textures of agates in sulfidic deposits). Zap. vsesoyuz. mineral. Obshch., 1974, 513–523. (in Russian)