Geology, published online on 6 November 2015 as doi:10.1130/G37276.1

Extrinsic forcing of plant ecosystems in a large igneous province: The Columbia River flood basalt province, Washington State, USA

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ABSTRACT

Volcanism associated with large igneous provinces (LIPs) has been implicated in both global climate and environmental change. To determine the impact of LIP volcanism on plant ecology we have examined plant community succession in sedimentary interbeds of the Columbia River flood basalt province (CRBP; northwest United States). Interbasaltic vegetation is characterized by primary succession communities that inhabit fresh lava surfaces until terminated by the next eruptive event, and it is assumed that longer volcanic hiatuses should lead to more mature plant communities. This expected succession trajectory is contradicted by palynological data that show that seral succession declines during the phase of waning CRPB volcanism and prolonged interbed intervals. Frequent volcanic activity and increased deposition of Snake River Plain hotspot ashes during this phase resulted in ecological disturbance of intralava field vegetation. Together with geochemical proxies from interbed sediments, this suggests that CRBP flora was largely driven by extrinsic forcing, and implies that LIP volcanism of similar scale and magnitude to that of the CRBP had a limited environmental impact. This study supports the theory that past biotic extinctions were triggered by numerous factors rather than a single geological event.

INTRODUCTION

Large igneous province (LIP) volcanic activity is considered to have directly or indirectly triggered global climate change and mass extinction events (Self et al., 2006; Bond and Wignall, 2014); however, the effect of LIP volcanism on both global and regional plant ecosystems is poorly constrained. Analysis of the composition and structure of modern plant communities on Krakatau (Indonesia; Whittaker et al., 1989) and ancient plant communities of the Miocene Columbia River flood basalt province (CRBP) (northwest United States) and Paleogene North Atlantic Igneous Province (Jolley, 1997; Jolley et al., 2008) indicates a strong relationship between duration of volcanic quiescence and plant seral succession (Jolley, 1997). This suggests that longer hiatuses in eruptive activity will be associated with more mature seral successions proximal to the volcanic center.

Testing the relationship between interflow field quiescence and plant seral succession status required an LIP with a relatively robust chronostratigraphic framework of eruptive events. The CRBP provides such a framework allied to well-developed and mapped sedimentary interbeds. For this study, fluvial and lacustrine interbed sediments were examined in the CRBP in Washington State, USA (Fig. 1). CRBP volcanic evolution is characterized by gradually decreasing eruption periodicity and eruption volumes, accompanied by longer periodicities between eruption events (Reidel et al., 2013). CRBP formation should thus be associated with more mature plant successions during the waning phase of volcanic activity.

Characterization of the interbasaltic plant succession and correlation with both local ecological conditions and extrinsic factors will provide important constraints on the drivers of plant ecosystems within volcanic terrains. A better understanding of ancient plant ecological processes and controls within LIPs is crucial to assess the effect of volcanic eruptions on ecosystems as well as the environmental impact at both local and global scales.

GEOLOGICAL SETTING

The CRBP is located within the backarc basin of the high Cascade Range in the northwest United States. Flood basalt volcanism began in the late Burdigalian on the Oregon plateau and was accompanied by rhyolitic to andesitic volcanism of the Cascade volcanoes and the Snake River Plain (SRP) (Camp and Ross, 2004). Flood basalt flows of the CRBP and the Oregon plateau are assigned to the CRBG. Eruption of the CRBG commenced at 16.72 ± 0.21 Ma with emplacement of the Steens Basalt, and continued until the early Messinian with eruptions along the Chief Joseph dike swarm, which produced the Imnaha, Grande Ronde, Wanapum, and Saddle Mountains Basalts (Reidel et al., 2013). A second northward migration trend exists along the Monument dike swarm, from which the Picture Gorge Basalt and Prineville Basalt erupted (Camp and Ross, 2004). Eruption of the Steens, Imnaha, and Grande Ronde Basalts marked the main phase of flood basalt volcanism, characterized by high eruption rates and volumes. This initial phase was followed by a progressive decrease in volcanic activity

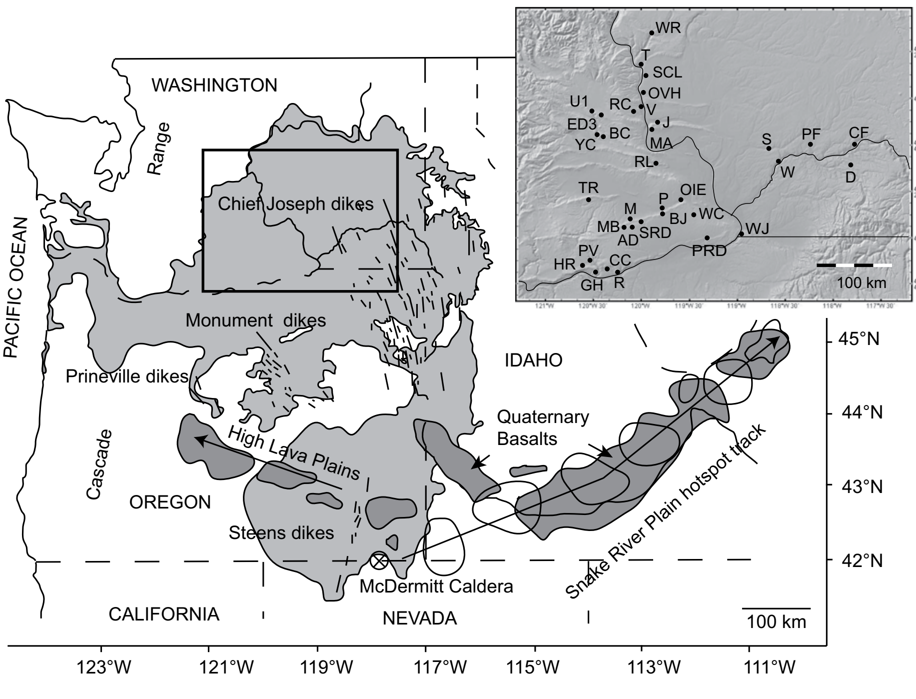

Figure 1. Location of the Columbia River flood basalt province (modified after Reidel et al., 2013), and migration of adjacent High Lava Plains and Snake River Plain hotspot track (Camp and Ross, 2004; Reidel et al., 2013). Abbreviations of plant communities are in Table DR1 (see footnote 1).

Data Repository item 2015371 | doi:10.1130/G37276.1

(Reidel et al., 2013), accompanied by an increase in interbed duration.

PALYNOFLORA

The palynological record within the interbeds was examined to reconstruct vegetation community dynamics throughout CRBP evolution. A total of 46 samples were taken from interbeds of the Douglas Creek (see Ebinghaus et al., 2014), Vantage, Squaw Creek, Selah, and Rattlesnake Ridge Members of the Ellensburg Formation. Palynological data were analyzed by performing detrended correspondence analysis (DCA), an ordination method widely used in multivariate statistical analysis of ecological data. DCA displays taxa along environmental gradients, which helps the user to distinguish ecological communities (Fig. 2; see Table DR1 in the GSA Data Repository[1]).

Sediments of the Douglas Creek Member were deposited within 4–8 k.y. (Jolley et al., 2008) between the R_2 and N_2 magnetostratigraphic units of the Grande Ronde Basalt (16.25 ± 0.27–15.46 ± 0.21 m.y.; Barry et al., 2013). Palynological investigations have yielded abundant *Quercoidites microhenrici* (oak), *Cupuliferoipollenites* (chestnut type), and *Intratriporopollenites* (basswood). DCA allied to botanical affinities of these floras indicated a late-successional mixed mesophytic forest. This is interpreted as the dominant vegetation community in the relatively dry, more elevated areas of the Douglas Creek Member paleosurface. During formation of the prolonged Vantage Member (<250 k.y., at 15.97 ± 0.4 m.y.; Barry et al., 2010), this community was replaced by mid-successional true swamp communities dominated by *Caryapollenites*, *Platycaryapollenites platycaryoides*, and *Momipites* (all walnut family). With ongoing CRBP volcanism, mature forest communities changed into mid-successional riparian to transitional swamp and early successional open floodplain communities adapted to higher moisture availability (Fig. 3). This is indicated by abundant *Alnipollenites* (alder), *Salixpollenites* (willow), and *Trivestibulopollenites paleobetuloides* (birch), accompanied by chlorophyceae algae (e.g., *Botryococcus braunii*) and disturbance-tolerant ruderals, such as sphagnaceaen mosses (*Stereisporites* spp.), club mosses, spike mosses, and polypodiacean ferns. Interbed duration times at this stage are estimated to have been <1 k.y. during deposition of the Squaw Creek Member (Jolley et al., 2008) and <500 k.y. during deposition of the Rattlesnake Ridge Member.

[1]GSA Data Repository item 2015371, Table DR1 (palynological data and weathering indices) and Table DR2 (XRF data of Columbia River flood basalt province, Cascade and Snake River Plain volcanic rocks), is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

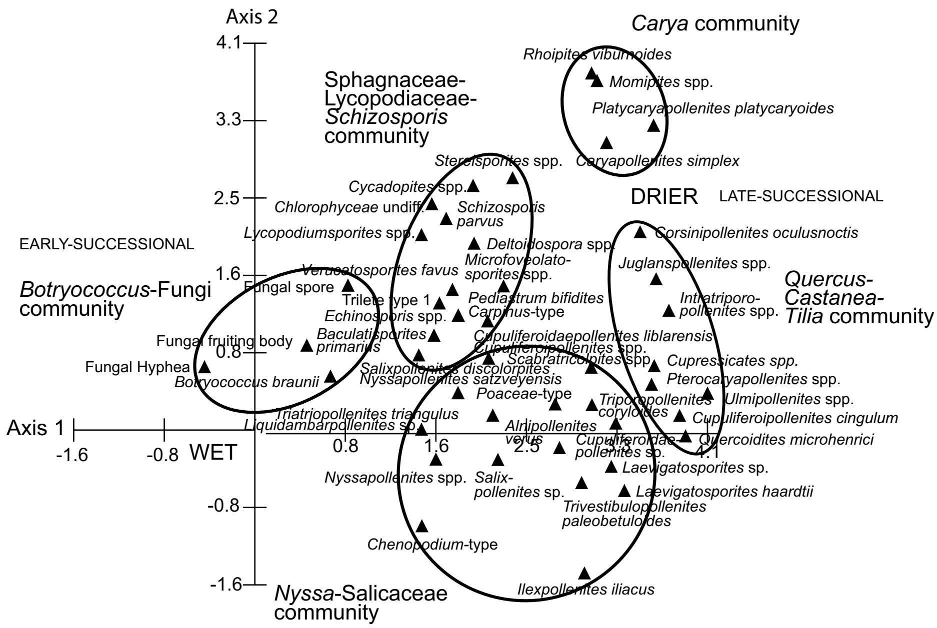

Figure 2. Detrended correspondence analysis scatter plot arranging palynological taxa along environmental gradients (axis 1 and 2). Taxa are grouped into five plant communities according to their botanical affinities, which are used to identify ecological habitats and seral successional status.

DISCUSSION

The observed distribution of plant communities through CRBP evolution does not support the proposed simple hypothesis of maturing plant successions in response to longer interbed intervals, and suggests repeated ecological disturbance during prolonged interbed formation. The deposition of thick fluvial sediments during the phase of waning volcanism indicates the formation of extensive drainage systems in the Rattlesnake Ridge Member (Ebinghaus et al., 2014). Lateral migration of river channels may be capable of cutting off large areas of vegetation, thereby hindering plant seral succession along river banks and floodplains, and favoring vegetation adapted to wetter soil conditions, as recorded from the late stage of CRBP volcanism. Sedimentary interbeds deposited on top of these lava flows vary considerably in thickness, suggesting the presence of topographic lows and highs within the lava field (Ebinghaus et al., 2014). Interbasaltic topography would have provided areas of distinctive soil formation, soil drainage, and habitats for communities adapted to different levels of moisture availability; this is at odds with the predominance of communities adapted to wet soils during the deposition of the Rattlesnake Ridge Member. The Douglas Creek Member is characterized by a migrating network of multiple small river channels and point bars (Ebinghaus et al., 2014) associated with a late-successional flora and high abundances of *Pinus* and *Picea*, bisaccate pollen that indicate a strong fluvial-derived input. Therefore, these data do not suggest a relationship between scale of lateral channel migration and floral succession.

CRBP volcanism could have affected plant succession through basaltic weathering and the eruption of acidic compounds (Vitousek, 2004; Self et al., 2006). The influence of volcanism can be assessed based on Ti/Al ratios, which indicate soil acidification and K/(Fe + Mg) ratios, which record the balance between detrital and mafic igneous input (Fantasia et al., 2015). The analysis of the chemical index of alteration (CIA-K; see Sheldon and Tabor, 2009) is used to determine the intensity of weathering related to climatic and/or acidic conditions (Fantasia et al., 2015). High K/(Fe + Mg) and low Ti/Al ratios in the Douglas Creek Member indicate little mafic input and low acidification; this suggests that basaltic weathering did not have a significant effect on plant succession. The Rattlesnake Ridge Member time of formation is characterized by increased mafic input and acidification; however, stable weathering intensity throughout CRBP time associated with variable Ti/Al ratios does not support the idea that acidification was related to CRBP eruptions (Fig. 3; Table DR2).

CRBP volcanic activity is implicated to have contributed to macronutrient availability through thermal fixation during short-term synvolcanic interbed formation proximal to the volcanic center. This is inferred from high abundances of the chlorophycean algae *Pediastrum bifidites*, which in modern environments requires high nitrate availability (Jolley et al., 2008). Thermal fixation of macronutrients through CRBP volcanism appears negligible in this study, because (1) *Pediastrum bifidites* is absent at this stage, and (2) the volcanic centers of the lavas underlying and overlying the Rat-

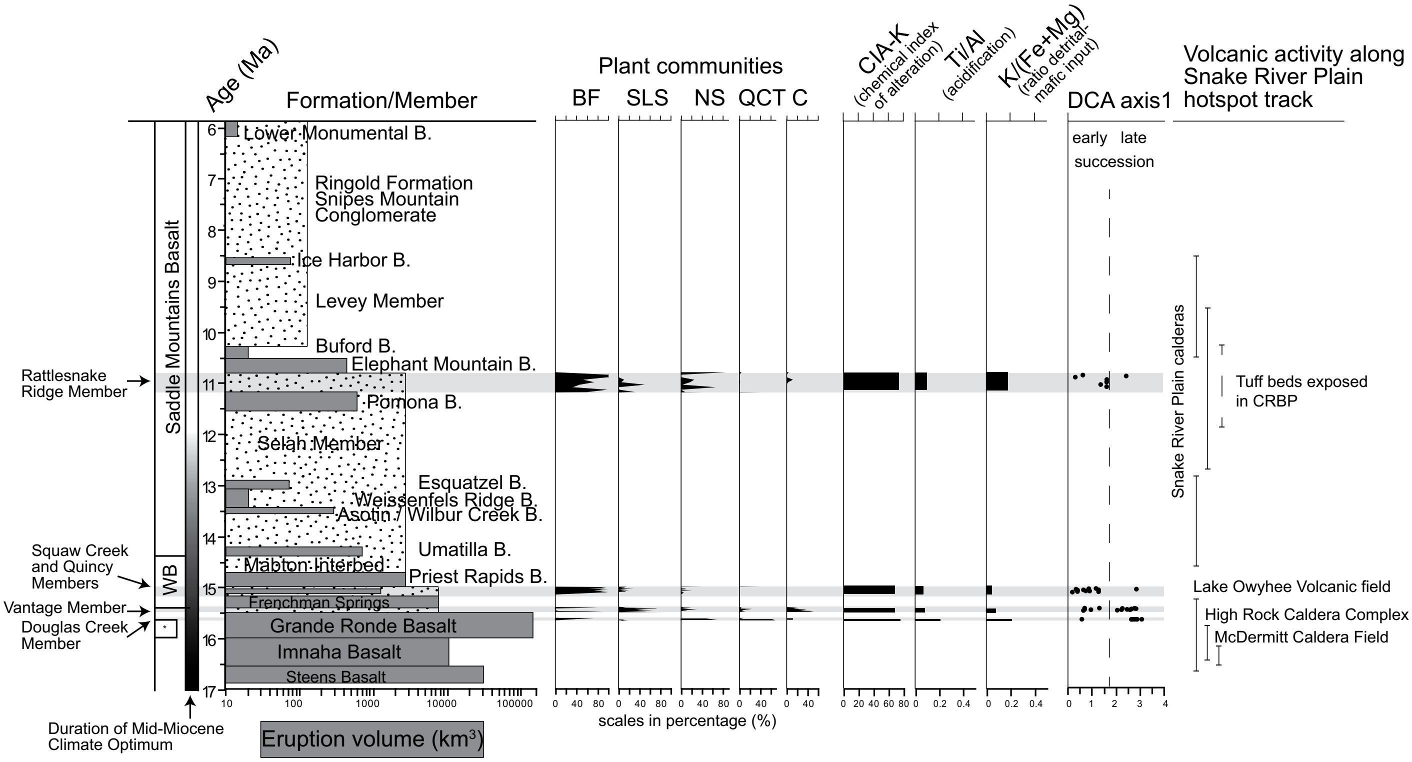

Figure 3. Correlation of Columbia River flood basalt province (CRBP) eruption volumes (adapted from Barry et al., 2013; Martin et al., 2013; Reidel et al., 2013), duration of mid-Miocene Climatic Optimum, environmental proxies, and seral plant succession. Detrended correspondence analysis (DCA) records a decline in successional status during the phase of reduced eruption volumes. Contemporary deposition of volcanic ashes derived from Snake River Plain (SRP) volcanism suggests strong correlations between interbasaltic seral plant succession and extrinsic volcanic activity. Eruption and depositional record of SRP volcanism is adapted from Coble and Mahood (2012) and Nash and Perkins (2012). *—Picture Gorge and Prineville basalts, WB—Wanapum Basalt, B.—basalt, BF—*Botryococcus*-fungi community, SLS—Sphagnaceae-Lycopodiaceae-*Schizosporis* community, NS—*Nyssa*-Salicaceae community, QCT—*Quercus*-*Castanea*-*Tilia* community, C—*Carya* community.

tlesnake Ridge Member (Pomona and Elephant Mountain basalts) are estimated to be >200–300 km away from the interbed localities.

Global climate warming during the Miocene (mid-Miocene Climatic Optimum; Zachos et al., 2001) may have affected plant communities (Fig. 3). The climatic optimum was followed by gradual surface cooling associated with growth of the East Antarctic ice sheet and expansion of the West Antarctic ice sheet ca. 10 Ma (Flower and Kennett, 1994). The decrease in temperature would have led to a shift of biomes from mixed mesophytic forests to broad-leaved evergreen forests characterized by higher dominance and less diversity (e.g., Wolfe, 1979). However, this trend cannot be recognized in the palynological record of the CRBP, which suggests a shift in the successional status, without any corresponding change in biome composition.

Severe ecological disturbance could have been caused by deposition of the volcanic ash beds that are exposed in the Rattlesnake Ridge Member (Ebinghaus et al., 2014). Their X-ray fluorescence chemical composition corresponds with the chemical composition of the Yellowstone hotspot lavas (SRP hotspot; data from Sarbas, 2015, GEOROC database; http://georoc.mpch-mainz.gwdg.de/georoc/Start.asp), as indicated by Nb-Zr-Y, Zr-SiO_2, and Nb-Zr ratios (Table DR2). Electron microscope analyses of the SRP hotspot ashes revealed high proportions of coarse glass shards ranging in diameter between 200 μm and 600 μm. Individual ash beds have a typical thickness of 0.25–0.5 m. The ecological effects of ash fall on flora are diverse, but depend mainly on the individual organisms, eruption type, seasonal timing, and volume, chemical, and physical properties of the erupted material (Thornton, 2000). Deposition of volcanic ash may cause burial, overloading, and defoliation (Ayris and Delmelle, 2012), and lowers or hinders photosynthesis and plant growth (Antos and Zobel, 1985). Volcanic ejecta may have long-term toxic effects on both flora and fauna through acid leachates, soil acidification, and acid rain (Kilian et al., 2006; Ayris and Delmelle, 2012). Nash and Perkins (2012) and Coble and Mahood (2012) recorded frequent eruptive activity of the SRP hotspot throughout the Miocene, with increased deposition of ashes within the CRBP during deposition of the Rattlesnake Ridge Member (Fig. 3). The timing of the seral successional stalling suggests a direct relationship between SRP volcanic activity and enhanced deposition of ash within the CRBP. This correlation together with the potential effects of explosive eruptions suggests that the SRP volcanism had a significant ecological impact on the Miocene CRBP flora by resetting plant succession after each major eruption event. SRP volcanism is likely to have caused short-term disturbances to climate and atmospheric patterns (e.g., Jones et al., 2007), as well as acid rain, as supported by increased acidification during the time of deposition of the Selah and Rattlesnake Ridge Members.

CONCLUSIONS

Investigations of the interlava palynoflora of the CRBP record a drastic successional decline during the phase of waning volcanism and longer interbed intervals (e.g., Rattlesnake Ridge Member). This trend does not support the hypothetical relationship between duration of volcanic hiatus and maturity of plant communities.

CRBP palynological investigations combined with several geochemical proxies, sedimentology, and lava field topography suggest that CRBP vegetation change was controlled by extrinsic SRP hotspot volcanism rather than intralava field processes and ecological conditions. Contemporary SRP volcanic activity and ash deposition affected plant ecosystem significantly by resetting plant seral succession. Climatic changes did not have an essential influence on CRBP biomes; this is supported by consistent weathering indices of interbed sediments. The important impact of SRP hotspot volcanism suggests that LIPs should be considered as interactive open environments. The successional decline throughout CRBP development implies that LIPs comparable to the CRBP are likely to have had a relatively limited impact on regional and global ecosystems, and that past major global environmental changes were driven by multiple factors rather than a single catastrophic event.

ACKNOWLEDGMENTS

We are grateful to Stephen Self and Stephen Reidel for support in the field, Richard Conrey and Laureen Wagoner for conducting X-ray fluorescence analyses, and Malcolm Hole for advice on igneous geochemistry. Reviews by Sylvie Bourquin, Robert Spicer, and an anonymous reviewer helped improve this paper. This research was partly funded by the Sindri Consortium.

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Manuscript received 21 August 2015
Revised manuscript received 15 October 2015
Manuscript accepted 15 October 2015

Printed in USA

Geology

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Geology published online 6 November 2015;
doi: 10.1130/G37276.1

Notes