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Late Holocene flood probabilities in the Black Hills, South Dakota with emphasis on the Medieval Climate Anomaly

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ABSTRACT

A stratigraphic record of 35 large paleofloods and four large historical floods during the last 2000 years for four basins in the Black Hills of South Dakota reveals three long-term flooding episodes, identified using probability distributions, at A.D.: 120–395, 900–1290, and 1410 to present. During the Medieval Climate Anomaly (~A.D. 900–1300) the four basins collectively experienced 13 large floods compared to nine large floods in the previous 800 years, including the largest floods of the last 2000 years for two of the four basins. This high concentration of extreme floods is likely caused by one or more of the following: 1) instability of air masses caused by stronger than normal westerlies; 2) larger or more frequent hurricanes in the Gulf of Mexico and Atlantic Ocean; and/or 3) reduced land covering vegetation or increased forest fires caused by persistent regional drought.

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1. Introduction

A detailed flood chronology obtained from late Holocene stratigraphy (Harden et al., 2011) for the Black Hills of southwestern South Dakota, located in the central US, is used to examine relations between short-term climate variations and extreme floods. Owing to the robust late-Holocene flood dataset from Harden et al. (2011) and relatively high resolution regional climate data, such correlations can be made for the first time for the Black Hills region of the US. Most of the existing paleoclimate studies in the region examine more general climatic conditions. Existing regional analyses from studies on dune fields (Nicholson and Swinehart, 2005; Schmeisser et al., 2010; Schwalb et al., 2010), lake sediment cores (Dean and Schwalb, 2000; Fritz et al., 2000; Laird et al., 1996; Shapley et al., 2005), tree-rings (Shapley et al., 2005; Weakly, 1943), and buried soils (Fredlund and Tieszen, 1997) indicate that in the Great Plains region, the late Holocene was a time of alternating wet and dry cycles resulting in changing forest vegetation characteristics. These changes likely resulted from large-scale shifts in atmospheric circulation patterns (Cook et al., 2011; Schmeisser et al., 2010). But the studies so far have not related the frequency and magnitude of extreme floods to such changes.

2. Study area

The Black Hills (Fig. 1) is a structurally uplifted ellipsoidal dome trending northwest to southeast, most likely formed during the Laramide orogeny about 60–65 million years ago (Redden and Lisenbee, 1996). Erosion has exposed the Precambrian crystalline core in the eastern-central part of the uplift, but the eastern and western flanks are formed of Paleozoic carbonate and sedimentary rocks. The average elevation of the Black Hills is about 1676 m with the highest peak being Harney Peak at 2207 m (Rothrock, 1945). Surrounding the Black Hills is rolling prairie that has a maximum elevation of about 1036 m.

Many of the major streams that drain the Black Hills area originate as headwater springs in a limestone plateau on the western side of the Hills and gain additional volume from precipitation, snowmelt, or additional springs at lower elevations. Most major streams drain into the plains to the Cheyenne River south and east of the Black Hills or to the Belle Fourche River (a major tributary of the Cheyenne) to the north and east. Peak flows derive mostly from snowmelt, prolonged rainstorms, or summer thunderstorms.

This study focuses on four major east draining streams, Elk, Boxelder, Rapid, and Spring Creeks, in the central Black Hills (Fig. 1). All four basins have headwater areas in the crystalline core where streamflow is very responsive to precipitation. As the streams flow east, they pass through mostly Paleozoic rocks, mainly limestone, where low flows are strongly controlled by interactions with an extensive groundwater system (Shepperd and Battaglia, 2002). Narrow, steep canyons characterize the basins as they drain through the Paleozoic rocks. All four drainage basins are predominately

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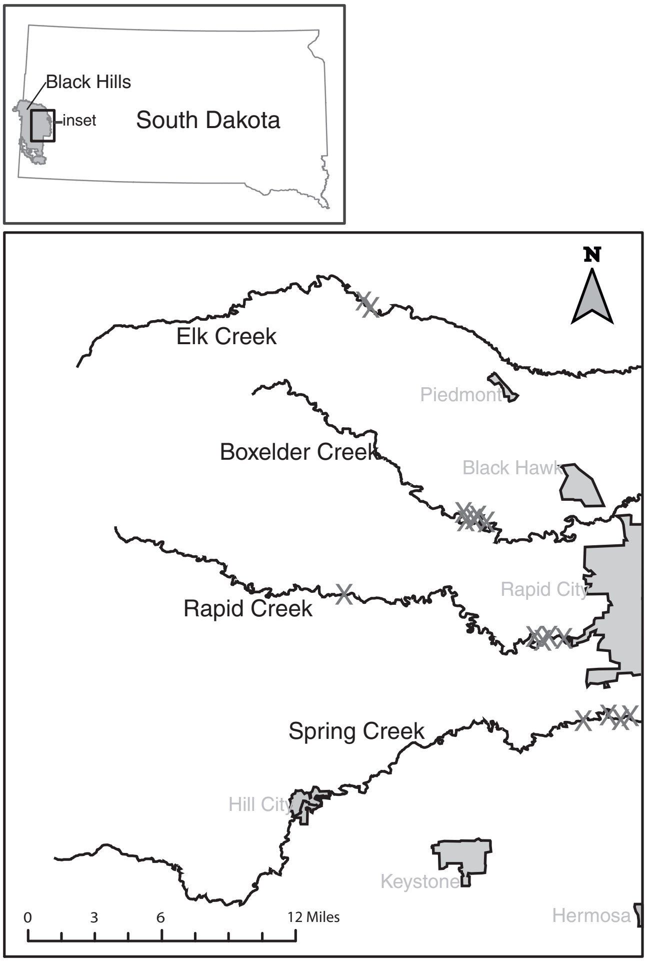

Fig. 1. Black Hills study area. The four streams in the Black Hills, South Dakota where radiocarbon dates were compiled. The dark gray x's indicate paleoflood stratigraphy sites from Harden et al. (2011) that are considered in this article.

forested with ponderosa pine and have limited urban development. Total drainage basin areas range in size from 384 mi^2 (992 km^2) for Rapid Creek at Rapid City to 126 mi^2 (326 km^2) for Boxelder Creek near Rapid City.

3. General climatology

The major moisture source for western South Dakota is air masses driven by continental-scale low-pressure circulation and moving northwest from the Gulf of Mexico. The Pacific Ocean is a secondary moisture source when atmospheric low pressure develops east of the Rocky Mountains (Karl et al., 1983). The Black Hills have a major orographic effect on storm patterns, temperature gradients, and precipitation totals (Spuhler et al., 1971). Because the Black Hills rise about 900–1200 m higher than the surrounding plains, they interrupt moisture flow from all directions, enhancing precipitation relative to the surrounding plains. The largest topographic gradients and greatest orographic effects are at the edges of the Black Hills (Driscoll et al., 2010).

In the summer, the principle source of precipitation is convective thunderstorms developing from warm moist air originating in the Gulf of Mexico. The thunderstorms gain intensity when they interact with east-moving cold fronts. Thunderstorms over the Black Hills are largely terrain-driven (Banta, 1990; Kuo and Orville, 1973). According to Banta (1990) and Hjemfelt et al. (1992), the Black Hills can provide the lifting effect required for storm initiation through three mechanisms; 1) orographic lifting effects, 2) thermally enhanced circulations, and 3) obstacle effects.

4. Modern peak streamflow

The Black Hills are very susceptible to large floods which pose a significant hazard for area communities. In 1972 flooding killed 238 people in and around Rapid City. Large floods in 2007 inundated parts of the small community of Hermosa (Driscoll et al., 2010).

Most peak flows in streams that drain the Black Hills occur during the summer months of May, June, July, and August when convective cells build over the foothills during the warm afternoons and can cause exceptionally strong rain-producing thunderstorms (Driscoll et al., 2010). These short-lived but intense convective rainstorms, including supercell thunderstorms, are common in the Black Hills (Dennis et al., 1973; Holm and Smith, 2008). Intense rainfall in conjunction with the steep topography and shallow soils can cause exceptionally large peak flows.

Strong storm events, basin orientation, soil properties, steep slopes, and vegetation cover all can affect peak flow-generation in the Black Hills. Although it is likely that the basin orientations and slopes have not changed substantially in the last several thousand years, it is possible that the frequency and strength of storm events, soil properties, and vegetation cover have changed or varied during this time. To evaluate this question, we have investigated a comprehensive stratigraphic record of large floods in the central Black Hills from Harden et al. (2011) relative to climatic and land cover.

5. Methods

Our analysis focuses on the last 2000 years in the east central Black Hills, where Harden et al. (2011) documented stratigraphic records of 38 large paleofloods (floods preceding observational and historical records) in the four study basins. By combining these stratigraphic records (and historic flood observations) with hydraulic and flood-frequency analyses, we identified 35 large floods (Table 1) with annual exceedance probabilities of 0.01 or less (equal to or great than the 100-year flood as defined in Harden et al., 2011). The 35 floods include five on Elk Creek, ten on Boxelder Creek, Fifteen on Rapid Creek, and five on Spring Creek.

These 35 floods are a subset of a larger population of floods identified in stratigraphic records extending back 6500 years in the Black Hills (Harden et al., 2011). This study focuses on the last 2000 years because the vast majority of the dated floods come from the relatively more complete stratigraphic records of the latest Holocene.

The chronology of these floods derives from 99 radiocarbon analyses of organic materials either within the flood slack-water deposits or in intervening or bracketing colluvial units. For flood deposits with multiple radiocarbon ages, we assign the youngest, consistent with the possibility of old carbon in our radiocarbon analyses. For flood deposits with bracketing ages, we assign the youngest maximum limiting age (in other words, the youngest age from deposits pre-dating the flood deposit). A few flood deposits also were dated by optically stimulated luminescence (OSL). In nearly all cases, the OSL results are similar to the radiocarbon ages; however for consistency, only results from radiocarbon dates were used in this study.

In addition to the stratigraphic record of flooding, we also consider historical floods. For this study, the historical period is considered to be after the first historical account of flooding in the area in 1877. Four such historical floods had peak discharges exceeding the 100-year flood discharge for their respective drainages. Three of these were the catastrophic 1972 flood (on Rapid, Spring, and Boxelder Creeks), and the other was in 1907 on Boxelder Creek.

All radiocarbon dates (Table 1) were calibrated to calendar years with OxCal version 4.1 (Bronk Ramsey, 2009; Bronk Ramsey et al., 2001). Oxcal uses a probability-based method for estimating calendar ages from radiocarbon ages (and their uncertainties), conveniently summarized by probability distribution functions with respect to calendar years. Thus, each of the 35 radiocarbon dated floods has associated