Prehistoric earthquake history revealed by lacustrine slump deposits

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ABSTRACT

Five strong paleoseismic events were recorded in the past 15 k.y. in a series of slump deposits in the subsurface of Lake Lucerne, central Switzerland, revealing for the first time the paleoseismic history of one of the most seismically active areas in central Europe. Although many slump deposits in marine and lacustrine environments were previously attributed to historic earthquakes, the lack of detailed three-dimensional stratigraphic correlation in combination with accurate dating hampered the use of multiple slump deposits as paleoseismic indicators. This study investigated the fingerprint of the well-described A.D. 1601 earthquake ($I = VII–VIII$, $M_w \sim 6.2$) in the sediments of Lake Lucerne. The earthquake triggered numerous synchronous slumps and megaturbidites within different subbasins of the lake, producing a characteristic pattern that can be used to assign a seismic triggering mechanism to prehistoric slump events. For each seismic event horizon, the slump synchronicity was established by seismic-stratigraphic correlation between individual slump deposits through a quasi-three-dimensional high-resolution seismic survey grid. Four prehistoric events, dated by accelerator mass spectrometry, ^{14}C measurements, and tephrochronology on a series of long gravity cores, occurred at 2420, 9770, 13,910, and 14,560 calendar yr ago. These recurrence times are essential factors for assessing seismic hazard in the area. The seismic hazard for lakeshore communities is additionally amplified by slump-induced tsunami and seiche waves. Numerical modeling of such tsunami waves revealed wave heights to 3 m, indicating tsunami risk in lacustrine environments.

Keywords: earthquake record, slumps, lacustrine sedimentation, tsunami, seismic stratigraphy.

INTRODUCTION

Earthquake recurrence intervals are important factors in seismic hazard assessment, but they are often poorly determined. In areas with low deformation rates, mainly intraplate regions, the recurrence intervals of strong earthquakes usually exceed the time span covered by historical records, so geologic records have to be investigated.

Synchronicity of deformation at different locations is one of the basic concepts to establish a paleoseismic event catalog (Ettensohn et al., 2002). Thus, correlation and dating of paleo-earthquake attributes, such as active faults, soft-sediment deformation features, and paleoliquifaction structures, is crucial, but often difficult to achieve (Greb and Dever, 2002). The temporal and spatial continuity of lake sediments makes them a powerful high-resolution archive to reconstruct the succession of large prehistoric seismic events.

Numerous studies report subaqueous mass movements that were triggered by historical earthquakes both in various lacustrine (Siegenthaler et al., 1987; Shilts and Clague, 1992; Niemi and Ben-Avraham, 1994; Chapron et al., 1999) and marine environments (Perissoratis et al., 1984; Syvitski and Schafer, 1996; Nakajima and Kanai, 2000). Similar mass movements can, however, be produced by aseismic processes as well (Siegenthaler and Sturm, 1991), and synchronicity of multiple features is the key to infer a regional seismic trigger mechanism. Kastens (1984) and Adams (1990) postulated this synchronicity for a series of turbidites by lithological and statistical correlation between piston cores, respectively. Our investigation proposes a new approach, which, in addition to previous outcrop and core studies, uses a complete quasi-three-dimensional seismic stratigraphy calibrated by ^{14}C dating in order to prove the synchronicity of paleoseismic events. This allows us to use the synchronous occurrence of multiple paleoslumps in lacustrine sedimentary sequences as a key to recognize strong prehistoric earthquakes and to explain the reported occurrences of large lake waves and seiches.

According to historical data, central Switzerland is one of the most active seismic areas of central Europe. Three events with $I = VII–VIII$ and $M_w > 5.5$ have been chronicled during the past millennium (Fig. 1); the strongest occurred A.D. 1601 (Swiss Seismological Service, 2002). Seismicity in the region, however, has been very low during the instrumental period. To extend this earthquake catalogue to prehistoric time, the sediments in Lake Lucerne provide an ideal archive. It is a perialpine lake of glacial origin at the northern border of the alpine range adjacent to the Swiss molasse basin (Fig. 1). The lake has a total surface of 116 km^2 and is fed by four main tributaries. It consists of seven subbasins, which differ in morphology, size, and hydrology. In order to minimize effects of spontaneous slumping due to overloading and oversteepening, this study concentrated on the northwestern subbasins, which lack major deltas and have relatively low sedimentation rates.

SLUMPS AND MEGATURBIDITES ON SEISMIC SECTIONS

The basin fill of Lake Lucerne was imaged with a dense grid of high-resolution seismic profiles (3.5 kHz pinger source) totaling >300 km (Figs. 2 and 3A). Numerous slump bodies occur throughout the

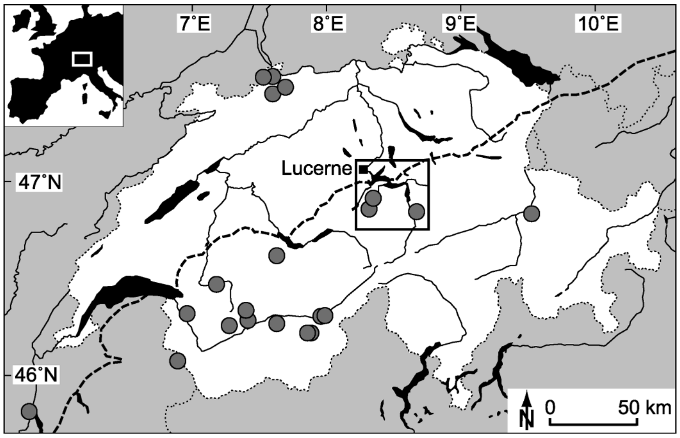

Figure 1. Earthquake catalog of Switzerland (Swiss Seismological Survey, 2002). Catalog is based on macroseismic and instrumental data from period A.D. 250–2001. Gray dots represent epicenters of earthquakes with $M_w > 5.5$. Black box indicates study area, which includes Lake Lucerne and city of Lucerne situated on outflow River Reuss. Northern alpine front is marked with dashed line.

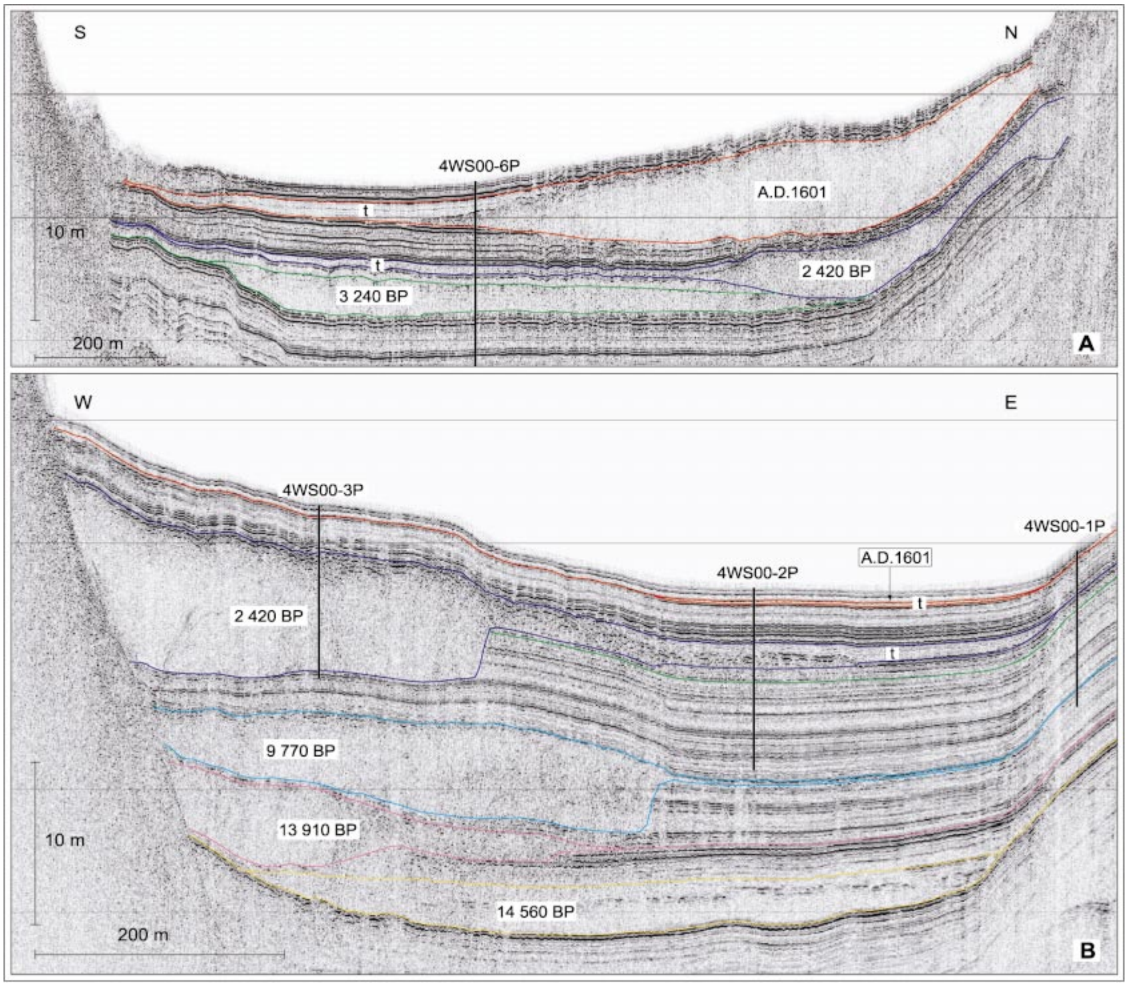

Figure 2. 3.5 kHz seismic profiles across (A) Vitznau and (B) Chrütztrichter subbasins of Lake Lucerne. For exact location of profiles, see Figure 3A. Discussed event horizons with related slump deposits and megaturbidites (t) are outlined in color. Ages: BP is calendar yr B.P. Vertical black lines indicate position of piston cores.

subsurface, as shown on seismic sections from two different subbasins (Fig. 2). Regular, undisturbed sediment consisting of faintly laminated mud with a few intercalated turbidite deposits produces continuous reflections in the seismic image. In contrast, the heavily disturbed slump deposits show a chaotic to transparent seismic facies, lacking continuous reflections. Deformation often is not restricted to the transported slope sediment, but also includes folding and thrusting of the marginal basin sediments, which become covered by the slump masses. The lower slump boundary, as detected on the seismic sections, consequently represents a lower limit of deformation and not a chronostratigraphic boundary or a scour surface. In the deepest part of the basin, slump deposits are typically overlain by a layer as thick as 2 m (denoted by t in Fig. 2) that is acoustically transparent and that consists of homogeneous mud with a graded silty to sandy base. We interpret these features as megaturbidites (Bouma, 1987), also referred to as homogenites (Kastens and Cita, 1981; Siegenthaler et al., 1987; Chapron et al., 1999) or seismoturbidites (Nakajima and Kanai, 2000). They consist of redeposited sediment that became suspended in the water column during the slumping, tsunami, and seiche action.

A.D. 1601 EARTHQUAKE AND ITS SIGNATURE IN LAKE LUCERNE

On 18 September 1601, central Switzerland was hit by one of the largest known earthquakes in central Europe (I = VII–VIII, $M_w \sim 6.2$; Swiss Seismological Service, 2002). Several towers in Lucerne were destroyed, and Renward Cysat, the registrar of Lucerne at that time, reported in his chronicle, ‘‘What scared people most was that the out flowing river Reuss flowed back into Lake Lucerne so that the riverbed between the two parts of the city almost became dry and several people could cross it by foot, before the water again vehemently advanced towards the city’’ (Cysat, 1601, p. 884). As Cysat traveled along the lake’s shore, he recorded observations such as: ‘‘Ships had been thrown onshore . . . up to two halberds [~4 m] above the lake level. . . . Small islands and shoals had disappeared,’’ (p. 883) as did ‘‘entire houses with sleeping people’’ (Cysat, 1601, p. 887). In Lucerne, the cyclic oscillation of lake level (seiche) had a period of 10 min and an estimated amplitude of 1–2 m (Cysat, 1601; Siegenthaler et al., 1987). An earthquake of this magnitude could not have directly caused such massive water movements that lasted several hours. In fact, Siegenthaler et al. (1987) linked these large-scale water movements of A.D. 1601 to two large slump deposits in the subsurface of Lake Lucerne.

These slumps, which occurred during the historic A.D. 1601 event, can be used to calibrate a signature of strong earthquakes in the subsurface of Lake Lucerne. The high resolution of our seismic surveys (10 cm in the vertical direction) allowed us to connect the top of each slump deposit to a distinct seismic-stratigraphic horizon. Such horizons represent isochrones that can be traced throughout the lake basins. By performing a seismic-stratigraphic analysis, we mapped the number of slump deposits coincident with a specific horizon. There are 13 inde-

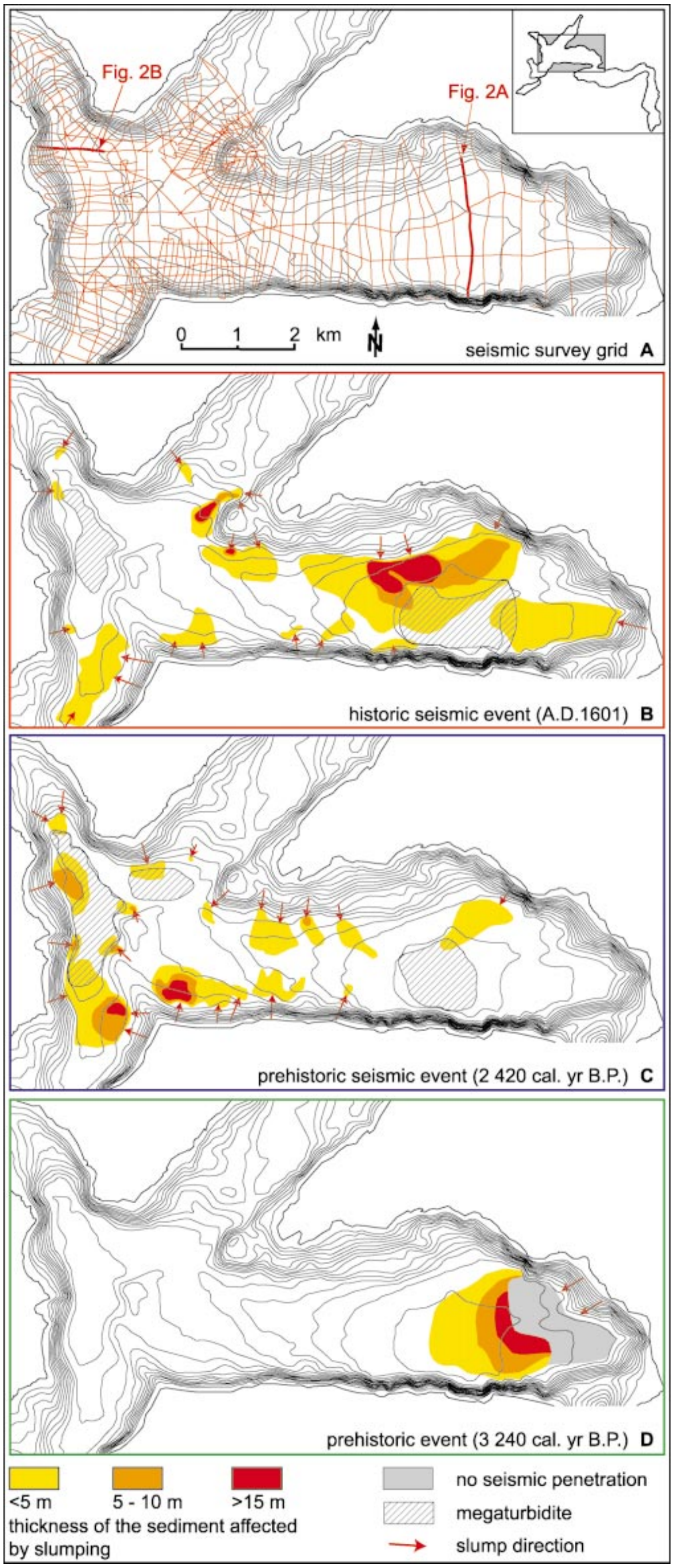

Figure 3. Slump deposits related to specific horizons. A: Grid of 3.5 kHz seismic profiles acquired for this study. B–D: Distribution and thickness of slump bodies corresponding to three event horizons shown in Figure 2A. Colors outlining boxes correlate to colors of event horizons. Hachured areas mark extent of megaturbidites directly overlying slump bodies. Bathymetric contour interval is 10 m.

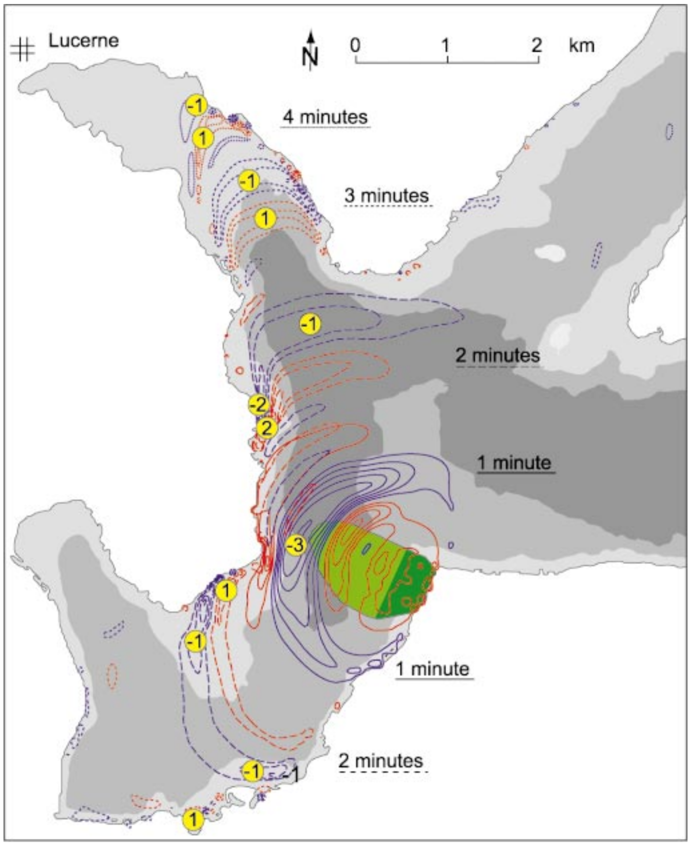

Figure 4. Map of western section of Lake Lucerne with contours of tsunami wave heights generated from modeled 2420 calendar yr B.P. slump. Dark green color indicates area of excavation; light green color marks area of sediment deposition. Blue lines contour depressed areas (wave valleys); red colors contour elevated areas (wave crests). Contour interval is 0.5 m. Wave positions are shown at 1 min intervals after initiation of slump. Yellow dots and numbers sample wave height in meters.

pendent slump deposits associated with the A.D. 1601 earthquake (Figs. 2 and 3B). Some of them are overlain by megaturbidites as thick as 2 m. The A.D. 1601 slumps and megaturbidites are located in two separate subbasins.

IDENTIFICATION OF PREHISTORIC EVENTS

To reconstruct the earthquake history of the area, we examined the lake's subsurface for older slump horizons, and deeper in the sedimentary sequence, we detected other horizons similar to the A.D. 1601 event. For example, the seismic-stratigraphic horizon of prehistoric event dark blue (see Fig. 2) is characterized by 16 independent slump bodies in two separate subbasins (Figs. 2 and 3C). The scars of the slump masses are located not only on the sides of the basins, but also on the slopes of a subaqueous hill cresting at $>$80 m water depth (Fig. 3C), where the influence of surface waves and flood events is negligible. The similarity with the horizon of the A.D. 1601 event, showing numerous coeval slumps and thick megaturbidites, points toward a strong earthquake as a regional triggering mechanism. In contrast, prehistoric event green (see Fig. 2) is characterized by only one huge slump deposit, with a volume of 17×10^6 m^3 (Figs. 2A and 3D). Because no other slump is found at the same seismic-stratigraphic level, the trigger mechanism was either an aseismic process or an earthquake of significantly smaller size than the A.D. 1601 event.

Including the A.D. 1601 event, five earthquake event horizons characterized by the occurrence of simultaneous, multiple slumping structures were identified. In order to date these horizons, eight gravity cores of 8–10 m length were recovered at key locations in two subbasins. Measurements of density, P-wave velocity, and magnetic susceptibility on these cores enabled accurate core-to-core and seismic data–to–core correlation. Each of the five horizons was dated independently one to four times by combining accelerator mass spectrometry (AMS), ^{14}C dating, sedimentation rate, tephrochronology (Hajdas et al., 1993, 1995), and seismic data–to–core correlation[1]. The resulting ages of the four prehistoric event horizons are 2420, 9770, 13,910, and 14,560 cal. yr B.P. We interpret these event horizons as the results of four major prehistoric earthquakes.

MODELING OF SLUMP-INDUCED TSUNAMI

To test the hypothesis that earthquake-triggered slumping induced the tsunami and seiche observed in A.D. 1601 and to quantify those water movements, we modeled the tsunami effect of one of the large slumps that occurred during the 2420 cal. yr B.P. event (Figs. 3C and 4). Seismic data revealed that a total of 11×10^6 m^3 broke away from a 0.3 km^2 excavation area and ran out into a 0.7 km^2 fan, leaving a 9-m-high scar in the lakebed. Knowing the 1500 m length of the slump and the initial slope (15°), simple kinematic arguments (Ward and Day, 2002) indicate that the slump could have reached a velocity of 15–30 m/s during its descent. To be conservative, we chose a slump velocity of 15 m/s. On the basis of these slump kinematics, the resulting vertical displacement of the water surface was calculated for different times by using classical linear water-wave theory (Ward, 2001). Figure 4 contours the tsunami height relative to the initial water level from 1 to 4 min after initiation of the slump. Within 1 min of failure, waves >3 m high are calculated to strike the shore directly across from the slump and start to run up the northwestern and southwestern arms of the lake. In the upper reaches of the northwestern arm, toward the city of Lucerne, the simulation forecasts wave heights of 1–1.5 m. Although this calculation includes the effects of shallow-water shoaling, it does not consider reflected waves that commonly are small unless the wave verges on shore at a near grazing angle. In such ‘‘funneling’’ geometries, added wave amplification due to multiple reflections might reach a factor of two. This simulation provides an estimate for the type and amplitude of tsunami expected from one of these subaqueous slumps.

Thus, slumping can trigger large lake waves in the range described by Cysat (1601); one could easily imagine the turbulent state of Lake Lucerne when numerous slumps triggered a series of tsunamis that became superimposed. Consequently, the risk caused by tsunamis and seiches should be part of a seismic hazard assessment, not only in marine, but also in lacustrine environments.

DISCUSSION AND CONCLUSION

Slump deposits associated with the A.D. 1601 earthquake show a characteristic pattern of numerous coeval slump deposits and associated megaturbidites. We consider such a widespread distribution of slump deposits as a key criterion for assigning a seismic triggering mechanism to a slump event rather than size. A detailed analysis of the older sedimentary subsurface of Lake Lucerne revealed four similar slump horizons with such depositional patterns indicative of seismic triggering. Thus, our data show that central Switzerland has been affected at least five times by strong earthquakes during the past 15 k.y. The time spans between those events appear to be highly variable.

The ability to identify prehistoric slump deposits triggered by strong seismic shaking opens up a broad field for paleoseismological investigations, because slump deposits have been related to historically described earthquakes in various lacustrine and marine environments and because they can be relatively easily detected from high-resolution seismic profiles and cores. In areas with low deformation rates, usually little is known about active faults, and the seismic potential is often underestimated. Lake deposits can record the effect of seismic shaking at a specific location, independent of the exact position of faults. Similar studies in neighboring lakes may reveal estimates of magnitudes and epicenters of past earthquakes.

ACKNOWLEDGMENTS

We thank Katrin Monecke for her help during field work, Robert Hofmann and Urs Gerber for technical support, and Gabriela Schwarz, Arnfried Becker, and Michael Sturm for discussions of historical and geologic data. Comments and suggestions of the reviewers Mervin J. Bartholomew and Frank R. Ettensohn improved and completed the manuscript. This is contribution 1249 of the Institute of Geophysics, ETH Zurich. The study was supported by the project PALEOSEIS (Swiss National Fond and Swiss Commission for the Safety of Nuclear Installations).

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Manuscript received June 17, 2002
Revised manuscript received August 28, 2002
Manuscript accepted September 6, 2002

Printed in USA

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[1] GSA Data Repository item 2002133, Dating of event horizons, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA, editing@geosociety.org, or at www.geosociety.org/pubs/ft2002.htm.