Kinematic evidence for downdip movement on the Mormon Peak detachment

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ABSTRACT

The Mormon Peak detachment is considered to be one of the best examples of a rooted upper crustal detachment fault that propagated through the brittle crust at a low angle. The hanging wall of the detachment today consists of a number of isolated blocks that have been interpreted as remnants of a once-contiguous extensional allochthon. Here we present the results of a new study of directional indicators from the basal surfaces beneath these blocks. These measurements do not agree with the long-standing interpretation of a S75°W movement direction for the detachment hanging wall. Instead, the most recent movement on each section of the detachment took place approximately parallel to the present downdip direction. We conclude that the Mormon Peak detachment is best explained as the basal surfaces to a series of rootless gravity slides.

Keywords: detachment faults, Basin and Range Province, gravity sliding, Mormon Peak detachment, crustal extension.

INTRODUCTION

The recognition of marked contrasts in metamorphic grade across detachment faults in metamorphic core complexes of the western United States (e.g., Crittenden et al., 1980) inspired the idea that large amounts of extension might be accommodated by regional low-angle normal faults. The Mormon Mountains of southeastern Nevada (Fig. 1) were instrumental to the general acceptance of this model in brittle rocks that lack evidence for mylonitization or for comparable coeval magmatism (Wernicke, 1981; Wernicke et al., 1985). Several workers later questioned the interpretation of large planar detachment faults (Bohannon et al., 1993) and extreme extension (Anderson and Barnhard, 1993; Carpenter and Carpenter, 1994; Anders et al., 2006) in the Mormon Mountains region. This paper provides pertinent new data from the less well-studied northern Mormon Mountains. We show that stratal and fault orientation data that have been used previously to ascertain the direction of hanging-wall motion cannot be uniquely interpreted in the Mormon Mountains and that kinematic indicators measured on the detachment surface instead reveal a motion direction approximately parallel to the present-day local downdip direction. These data are consistent with an earlier, but generally ignored, interpretation of the Mormon Peak detachment comprising the basal surfaces to a series of rootless block slides (Carpenter and Carpenter, 1994).

EXTREME EXTENSION HYPOTHESIS

The Mormon Mountains are at the transition between the highly extended Basin and Range Province to the west and the little extended Colorado Plateau to the east. The most enigmatic feature of the range, the Mormon Peak detachment (Wernicke, 1981), is a sharp, locally planar surface that cuts nearly all other structures, dips on average ~20° away from the center of the range, and generally places younger, mostly limestone Paleozoic strata from the hanging wall of the Mormon thrust on top of older, mostly dolostone Paleozoic strata from the footwall of the same thrust (GSA Data Repository Fig. DR1[1]). Wernicke (1981) interpreted the Mormon Peak detachment as an exhumed, rooted, low-angle normal fault. He determined, from a reconstruction of stratigraphic cut-off angles, that the detachment had originated with a dip of 20–25°W (Wernicke et al., 1985). The Mormon Peak detachment was interpreted as the oldest of three nested detachment faults in the region. High-angle faults cutting the Mormon Peak detachment were inferred to sole into a structurally lower, younger detachment called the Tule Springs detachment; the Castle Cliff detachment is the deepest and most eastern. In his model, movement on these lower faults caused doming and tilting of all older features, which led to the present-day arrangement in which the Mormon Peak detachment dips west on the west side of the central Mormon Mountains, and east on the east side (see cross sections in Wernicke et al., 1985). Wernicke and coworkers assigned ~23 km (Axen et al., 1990) of S75°W-directed extension (Wernicke et al., 1988) to the Mormon Peak detachment, and inferred that overall extension in the region between the Meadow Valley Mountains to the west and the Beaver Dam Mountains to the east was >110%.

ALTERNATIVE HYPOTHESES

Other workers have queried the interpretation of the Mormon Peak detachment as the primary expression of crustal extension. Carpenter and Carpenter (1994) combined industry seismic reflection profiles with gravity data to argue that the interpretation of regional detachment faults is inconsistent with subsurface geology. Anderson and Barnhard (1993) examined outcrops in the southern Mormon Mountains and Beaver Dam Mountains, and concluded that low-angle normal faults exposed in these ranges steepen at depth, accommodating 25%–30% extension across the area. Bohannon et al. (1993, p. 515) reevaluated available seismic reflection data from the basin to the southeast of the Mormon Mountains, and found "no evidence for large planar detachment faults," but inferred 56%–72% extension across more steeply inclined planar and listric faults. Each of these papers presented cross-sectional interpretations that differ substantially from those of Wernicke et al. (1985) and Axen et al. (1990). Anders et al. (2006) argued that the character of deformation along the Mormon Peak detachment shows no evidence for repeated motion, such as crosscutting veins, healed microfractures, or multiple generations of breccia formation. Rather, the observed style of deformation is remarkably similar to that found at the base of catastrophic landslides.

KINEMATIC INDICATORS

Kinematic data from the Mormon Peak detachment are radially distributed (Fig. 1; Table DR1 [see footnote 1]). The indicators correspond more closely with the local dip direction of the detachment, defined as the normal to the confined structure contour nearest to the point at which the measurement was made, than with the previously published S75°W motion direction. Several indicators are perpendicular to this direction.

Kinematic indicators were recorded at the base of a microbreccia layer directly above the detachment, or along the upper surface of the footwall rocks directly beneath the detachment.

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[1] GSA Data Repository item 2007057, Figures DR1, DR2, and DR3 (photographs of the detachment), Table DR1 (kinematic indicators recorded on the Mormon Peak detachment) and Table DR2 (dips measured on the Mormon Peak detachment), is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Geology, March 2007; v. 35; no. 3; p. 259–262; doi: 10.1130/G23396A.1; 3 figures; Data Repository item 2007057.

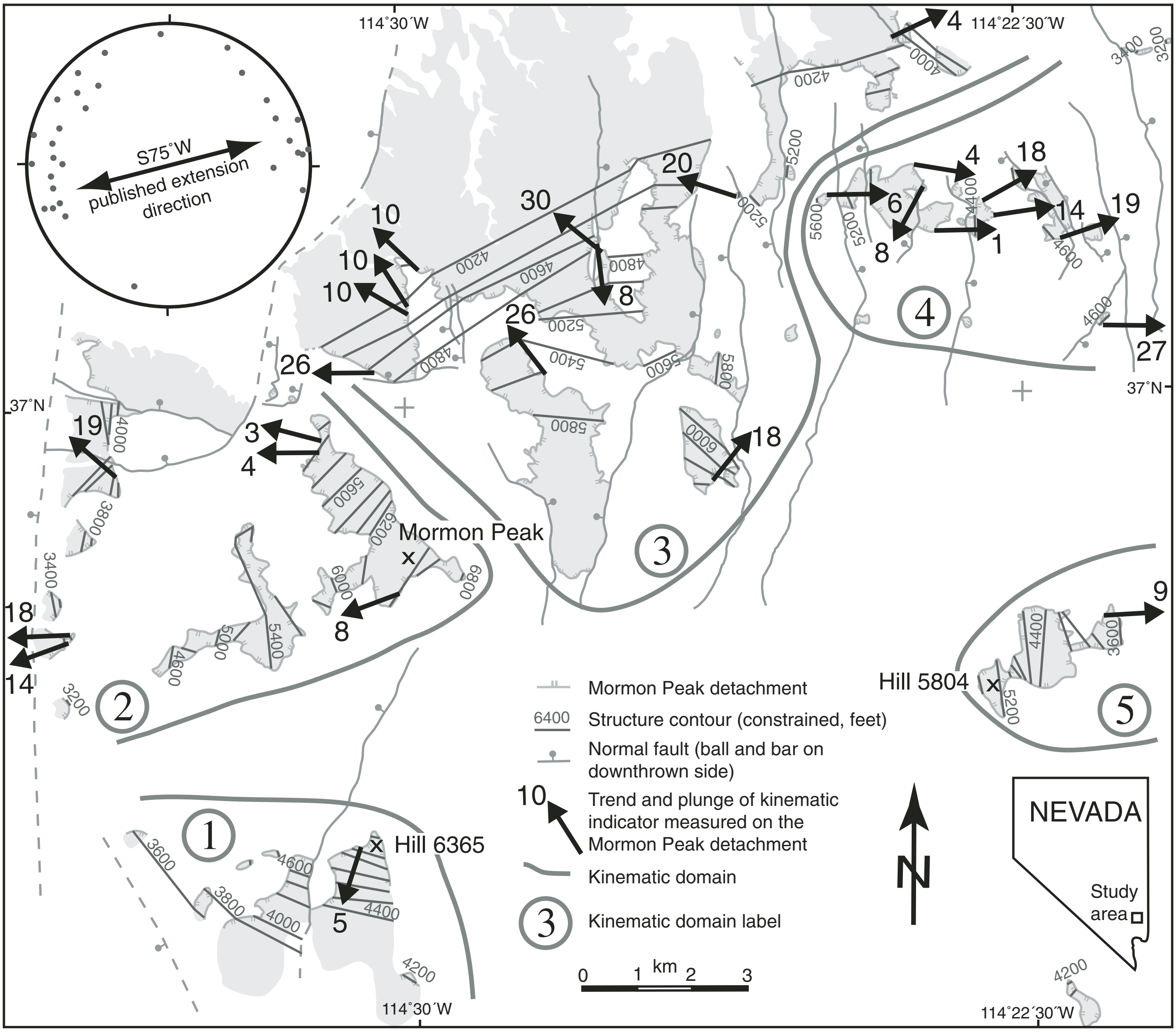

Figure 1. Generalized map displaying radial, downdip distribution of kinematic indicators on Mormon Peak detachment. Outcrops of detachment hanging wall are shaded. Only faults that cut detachment are shown. Constrained structure contours link two mapped outcrops of detachment. Inset equal-area projection shows difference between detachment striae (dots) and previously published S75°W extension direction. Geology south of Mormon Peak is generalized from Wernicke et al. (1985).

Axen (2004, p. 46) described the microbreccia layer as part of the footwall sequence, 'a thin (0–3m) zone of finer-grained "microbreccia" with a sharp, striated detachment fault surface at its top.' In the Mormon Mountains, however, this layer forms the base of the hanging-wall sequence; footwall deformation is restricted to a 1–10-m-thick autobreccia zone beneath the detachment (Anders et al., 2006).

The indicators measured include slickenlines and small-scale corrugations of the detachment surface (<5 m wavelength). Broader warping of the detachment was not used as a motion direction proxy because such deformation can be caused by younger faults and isostatic rebound. The slickenlines recorded correspond with the a-type and f-type striae of Means (1987). Ridges are generally as common as grooves, but it was not possible to assess Means's second criterion of congruent nesting of grooves and ridges, because no locality was found at which the base of the microbreccia and the top of the footwall are both striated. However, it seems reasonable to suggest that the striae were caused by asperities in the microbreccia plowing through the footwall. Slickenlines found on the base of the microbreccia layer therefore represent casts of the footwall grooves, after the footwall has been removed. Beutner and Gerbi (2005) reported similar observations from the base of the microbreccia layer above the Heart Mountain detachment. In the Mormon Mountains it is possible to determine the sense of motion from the slickenline trends at only two localities (1 and 18 in Table DR1; Fig. DR2 [see footnote 1]) where chattermarks are found. No oriented calcite fiber growth, thought to be indicative of repeated stick-slip motion (e.g., Ramsey and Huber, 1983, p. 259), has been observed along the detachment. As repeated stick-slip faulting would provide more opportunities for the creation of several generations of indicators, the paucity of directional slickenlines is consistent with a single episode of displacement along the detachment surface inferred from studies of the microbreccia layer (Anders et al., 2006).

HANGING-WALL BEDDING DIPS

The previously published detachment movement direction was based on a study of 277 hanging-wall bedding dips, from which an ENE extension direction was interpreted (Fig. 17 in Wernicke et al., 1985). This was refined to S75°W in Wernicke et al. (1988). The 230 dips

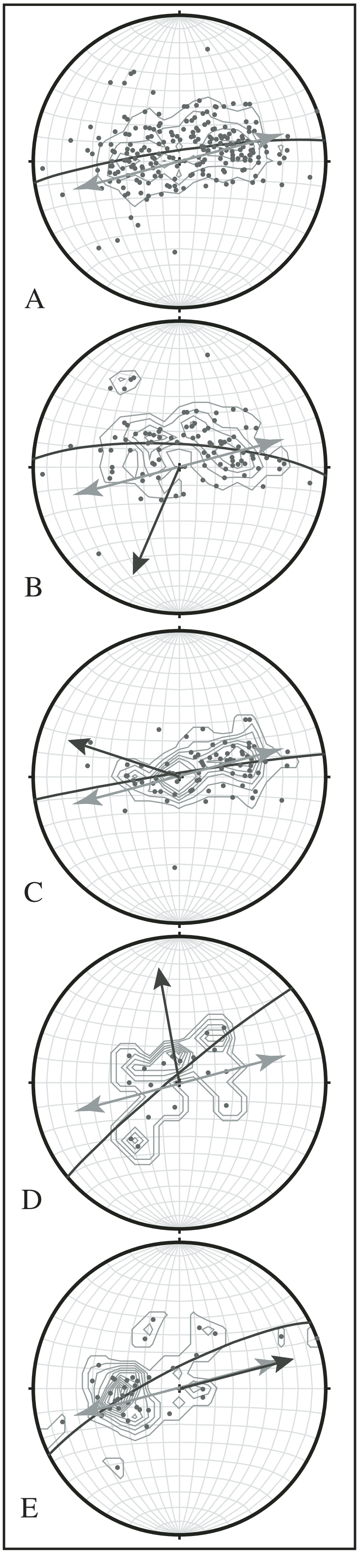

Figure 2. Lower hemisphere equal-area projections comparing difference between bedding tilts and local dip of Mormon Peak detachment. Double-headed gray arrows show inferred S75°W extension direction (Wernicke et al., 1988). Single black arrowhead shows average normal direction to structure contours in each region. Dots are poles to bedding. Gray great circles are best-fit girdles to poles. A: All dips, n = 230. B: Region 1, n = 92. C: Region 2, n = 81. D: Region 3, n = 18. E: Region 5, n = 40. Gray contours are 2%/1% area.

shown in the detachment hanging wall on the geologic map in Wernicke et al. (1985) can be broken down into various domains based on structure contour and kinematic indicator orientations (Fig. 1). In detail, the mean bedding dip in each domain is oriented as much as 20° from the inferred S75°W direction (Fig. 2). More important, bedding dip shows no relation to either the local dip direction of the Mormon Peak detachment or to the directions of kinematic indicators measured on the Mormon Peak detachment.

The original study (Wernicke et al., 1985) was based on the assumption of pre-extension stratal horizontality allowing all hanging-wall tilts to be related to Mormon Peak detachment motion. However, even rocks in the Mormon Mountains below the Mormon Peak detachment dip on average N80°E (Wernicke et al., 1985, p. 223). This part of the Basin and Range Province was deformed by roughly E-vergent thrusting during the Cretaceous (Axen et al., 1990), and then extended in a NE-SW direction during the Neogene (Wernicke et al., 1988). The NE- and SE-dipping rocks are therefore not solely related to motion on the detachment surface and hanging-wall bedding tilt directions cannot be used to ascertain a unique hanging-wall movement direction.

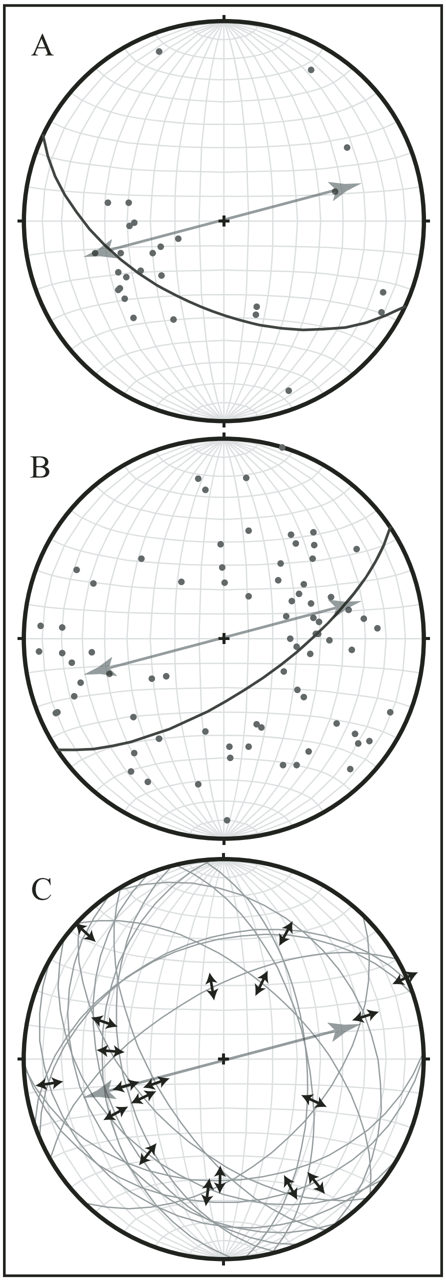

Figure 3. Lower hemisphere equal-area projections comparing differences between hanging-wall fault orientations and inferred S75°W movement direction (gray arrows; Wernicke et al., 1988). A and B show poles to faults of Mormon Peak detachment hanging-wall rocks. A: Region 2, n = 27. B: Regions 3 and 4, n = 78. C: Slickenlines (small arrows, n = 19) on fault planes (lines, n = 18) in all regions. Great circles in A and B are best-fit girdles to poles.

HANGING-WALL FAULT ORIENTATIONS

Orientations of hanging-wall faults also do not delimit the motion direction of the Mormon Peak detachment in the Mormon Mountains, although they have been used to interpret other detachments at nearby locations. In the Beaver Dam Mountains of southwestern Utah, a SW extension direction was interpreted from striated normal faults that generally terminate downward at the Castle Cliff detachment (Smith et al., 1987). Axen (1993) interpreted E-W movement on the Tule Springs detachment based on N-S–striking faults in the hanging wall. Data from rocks above the Mormon Peak detachment, however, show a dispersed pattern of fault orientations that illustrates the problems with this approach (Figs. 3A, 3B). While many faults trend approximately NNW-SSE, there is a wide range of other orientations. Kinematic data obtained from these faults show a radial distribution of movement directions (Fig. 3C), broadly similar to the pattern seen in Figure 1, and small rake angles indicate that some slickenlines formed obliquely from strike slip on high-angle faults. These data cannot be explained simply by a WSW-directed pattern of extension. We suggest that they may be due to downdip motion on the Mormon Peak detachment, during which changing stress orientations reactivated preexisting faults to accommodate strike slip, oblique slip, and even reverse slip as the blocks in the hanging wall rotated, internally extended, and laterally spread out downhill under the force of gravity. The preponderance of preexisting faults in the study area may help explain why the hanging wall is so macroscopically intact. The ability of such structures to absorb the manifold stresses generated by down-slope motion may have prevented the pervasive brecciation that is sometimes associated with large gravity slides (Yarnold and Lombard, 1989).

DISCUSSION AND CONCLUSIONS

Kinematic indicators measured on the basal surface of the Mormon Peak detachment demonstrate that the most recent movement occurred in an orientation approximately consistent with the local downdip directions of the detachment. We interpret this as evidence for the sloughing of large slide blocks away from a central high. Several discrete domains are delimited, suggesting that individual blocks moved at different times, although not necessarily over a protracted interval. Preexisting faults were reactivated and new faults were formed to accommodate this motion, but overall the slide blocks remained remarkably intact. Deformation was instead concentrated along a narrow zone of brecciated material that is much thicker above the detachment (10 to >100 m) than beneath it (1–10 m).

In an attempt to address the possibility that basal surfaces of large coherent gravity slides may have been mistaken for rooted normal faults (e.g., Boyer and Allison, 1987), Axen (2004) outlined four arguments with respect to the Mormon Peak detachment: none is compelling. First, he stated that there is no evidence for radial sliding. Our kinematic data for the Mormon Peak detachment provide ample evidence for radial downdip motion. Second, he claimed that there is no basin to the north and west into which hanging-wall rocks could have slid, and in a third, related argument, there was no high ground from which slides could have originated. A seismic profile to the north of the study area (Carpenter and Carpenter, 1994) and our mapping (Fig. 1) show that the west side of the Mormon Mountains is bounded by a high-angle normal fault, consistent with the present topography and the existence of an adjacent basin, and providing the free surface needed to rotate stresses and allow movement on the low-angle Mormon Peak detachment. Apatite fission-track ages show that range-bounding normal faults in the region were actively exhuming basement through the partial annealing zone (~4 km depth) from at least 17 Ma (Stockli, 1999). This provides ample time for the development of topography before movement on the Mormon Peak detachment, which cuts volcanic rocks as young as ca. 12 Ma (Axen et al., 1990). Finally, Axen (2004) noted that the Mormon Peak detachment does not steepen into a headwall scarp, and suggested that if anything, it is more gently inclined at higher elevations. However, measurements of Mormon Peak detachment dip display no trend with elevation (Fig. DR3; see footnote 1). This argument also fails to recognize that the Mormon Peak detachment represents at least five different slide events since the mid-Miocene. It is unrealistic to expect a steep headwall scarp or a highly dismembered toe area to have escaped erosion or burial in the intervening period. Instead these processes continue to shape the mountain range to the present day.

Examination of kinematic indicators measured beneath isolated blocks in the Mormon Mountains has allowed us to identify divergent components of downdip motion on surfaces that had previously been interpreted as a continuous surface beneath a large extensional allochthon. The application of this technique to other locations may permit the recognition of other coherent gravity slides that are currently interpreted as dismembered rooted faults, with corresponding implications for estimates of crustal extension.

ACKNOWLEDGMENTS

Our research in the Mormon Mountains was supported by the donors of the Petroleum Research Fund of the American Chemical Society, grants 32914-AC2 and 39709-AC8, and National Science Foundation grant 99-02782. We thank Robert Bohannon, Darrel Cowan, James Faulds, Marli Miller, and an anonymous reviewer for helpful critiques of earlier versions of this manuscript, and Jim Carpenter, Thorsten Nagel, John Cooper, David Rodgers, Peter Almasi, Celine Herweijer, Christine Metzger, and Sergen Ozbek for insightful discussions in the field. Lamont-Doherty Earth Observatory Contribution 6986.

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Manuscript received 26 September 2006
Revised manuscript received 9 November 2006
Manuscript accepted 14 November 2006

Printed in USA