Offshore evidence on the source of the 1998 Papua New Guinea tsunami: A sediment slump

Dave R. Tappin[1], Philip Watts[2], Gary M. McMurtry[3], and Takeshi Matsumoto[4]

[1]***British Geological Survey, Keyworth, Nottingham, United Kingdom***
[2]***Applied Fluids Engineering, Inc., Long Beach, California, U.S.A.***
[3]***School of Ocean and Earth Science and Technology, University of Hawaii, Honolulu, Hawaii, U.S.A.***
[4]***Japan Marine Science and Technology Center, Natsushima-cho, Yokosuka, Japan***

Abstract. The source of the local tsunami that struck the north coast of Papua New Guinea in July 1998 is controversial and is postulated as due either to a thrust or sediment slump. However, the results from five offshore surveys indicate the most likely source to be a sediment slump located in the eastern part of an amphitheater-shaped feature off of the Sissano Lagoon. No major reverse faulting has been observed. Within the amphitheater, seabed photographs indicate recent seabed movement in the form of fissures, brecciated cohesive sediment, and fresh rock talus deposits. The most recently slumped area has major fissures that are associated with fluid expulsion features such as shimmering in the water column and common chemosynthetic biotas. A multichannel seismic line across the amphitheater supports a slump source (Sweet and Silver, 2001). The convergent margin offshore of northern PNG is complex. The inner trench wall is actively subsiding. There are steep slopes and numerous faults with sharp scarp faces that displace both superficial sediment and basement. Deeply incised submarine canyons suggest that sedimentation rates are low. Sediment cores are homogeneous mud that is highly cohesive. The sediment fails retrogressively along rotational shears, with the shear planes nucleating along faults.

1. Introduction

The Sissano or Aitape tsunami that struck the north coast of Papua New Guinea (PNG) on 17 July 1998 left 2200 people dead and 12,000 homeless. Three villages were completely destroyed and four more badly damaged (Fig. 1) (Davies, 1998; Kawata *et al.*, 1999). The cause of the tsunami has been the subject of a comprehensive investigation that now includes survivors' accounts, onland study, offshore seabed imaging, seismological analyses, and computer simulations (Davies, 1998, 2000; Kawata *et al.*, 1999; Matsuyama *et al.*, 1999; Tappin *et al.*, 1999; Tappin *et al.*, 2001). However, the source of the tsunami has remained controversial. The most likely tsunami sources are a steeply dipping southward overthrust or a sediment slump. This paper presents the results of three offshore surveys conducted by the Japan Marine Science and Technology Center (JAMSTEC) and the South Pacific Applied Geoscience Commission (SOPAC). Data acquired in-

[1]British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham, NG12 5GG, United Kingdom (d.tappin@bgs.ac.uk)

[2]Applied Fluids Engineering, Inc., Mail Box #237, 5710 East 7th Street, Long Beach, CA 90803, U.S.A. (phil.watts@appliedfluids.com)

[3]School of Ocean and Earth Science and Technology, University of Hawaii, 1000 Pope Road, Honolulu, HI 96822, U.S.A. (garym@soest.hawaii.edu)

[4]Japan Marine Science and Technology Center, 2-15 Natsushima-cho, Yokosuka, Kanagewa, 237-0061, Japan (matsumoto@jamstec.go.jp)

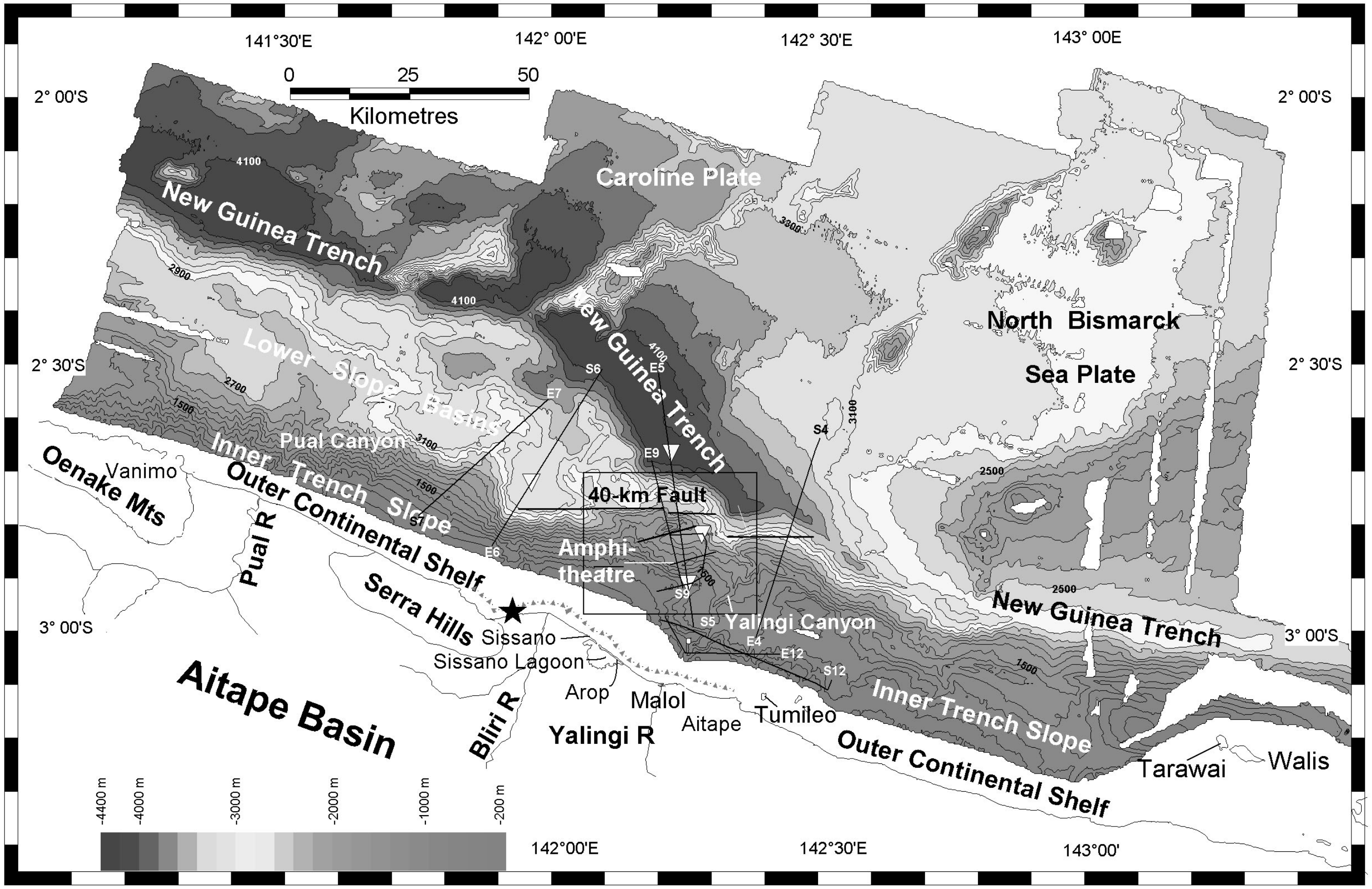

Figure 1: Bathymetry and main morphologic elements offshore of northern Papua New Guinea together with the main coastal locations and features. Solid black lines are faults. Filled triangles identify the area devastated by the 17 July 1998 tsunami. Black star is the most likely epicentral location of the 17 July 1998 earthquake. Open inverted triangles are sediment core locations. Light black lines are SBP profiles. Box is the area of Fig. 2.

cludes: multibeam bathymetry and sonar, high-resolution (4.2 kHz) seismic, sediment piston cores, rock samples, and seabed observational data.

2. Multibeam Bathymetry

The bathymetry shows the convergent margin off northern PNG to be complex. Several main structural elements are identified below (Fig. 1).

2.1 Continental shelf and inner trench slope

The continental shelf is up to 200 m deep, with significant along-strike (generally east to west trending) morphologic variation. The shelf narrows from a width of 10 km in the east to 5 km in the west. There is one large delta construction off Sissano Lagoon on the northeast margin of which is a subsided reef. Seaward of the shelf, water depths increase rapidly, and the inner trench slope is deeply incised by submarine canyons, several of which are large. The slope may be subdivided at the prominent Yalingi Canyon, located just offshore of Malol. To the east of this feature, the slope is narrow at 25–30 km and seabed gradients are steep. The slope to the west of the Yalingi Canyon is wider (>50 km) and the upper slope gradient is steeper than that to the east. There are lower slope basins with steep headwalls. The basins have planar floors that are gently back-tilted. Deeply incised submarine canyons on the upper part of the inner trench slope terminate in the basins.

2.2 Transition zone

Offshore of the Sissano Lagoon lies a transition zone between the eastern and western parts of the inner trench slope (Fig. 2). The lower part of the Sissano delta forms a prominent shallow water area. Below the delta there are several major scarp features with very steep gradients, averaging 45–50°. An amphitheater centered at 142.26°E, and lying between 800 and 2,200 m water depth is interpreted as formed by slumping and rotational faulting. Within this feature is the 5×5 km slump identified as the likely tsunami source (Tappin *et al.*, 1999, 2001). The amphitheater comprises an upper steep scarp, below which there is a bench or mound that is slightly elevated in the east (Fig. 2). Below this mound, seabed gradients again increase and a less pronounced scarp slope descends into a depression with an irregular floor. The northern margin of the amphitheater is a northeast-southwest trending upraised block that crests at 1,400 m water depth. The upraised block is bounded in the south by a 14-km fault (that downthrows to the south) and in the north by the east-west trending 40-km fault, that downthrows to the north (Fig. 2).

2.3 New Guinea Trench and Pacific Plate

The New Guinea Trench dissects the area. Its morphology varies along strike. In the east it is oriented ESE to WNW, is shallowest at 3000 m, and

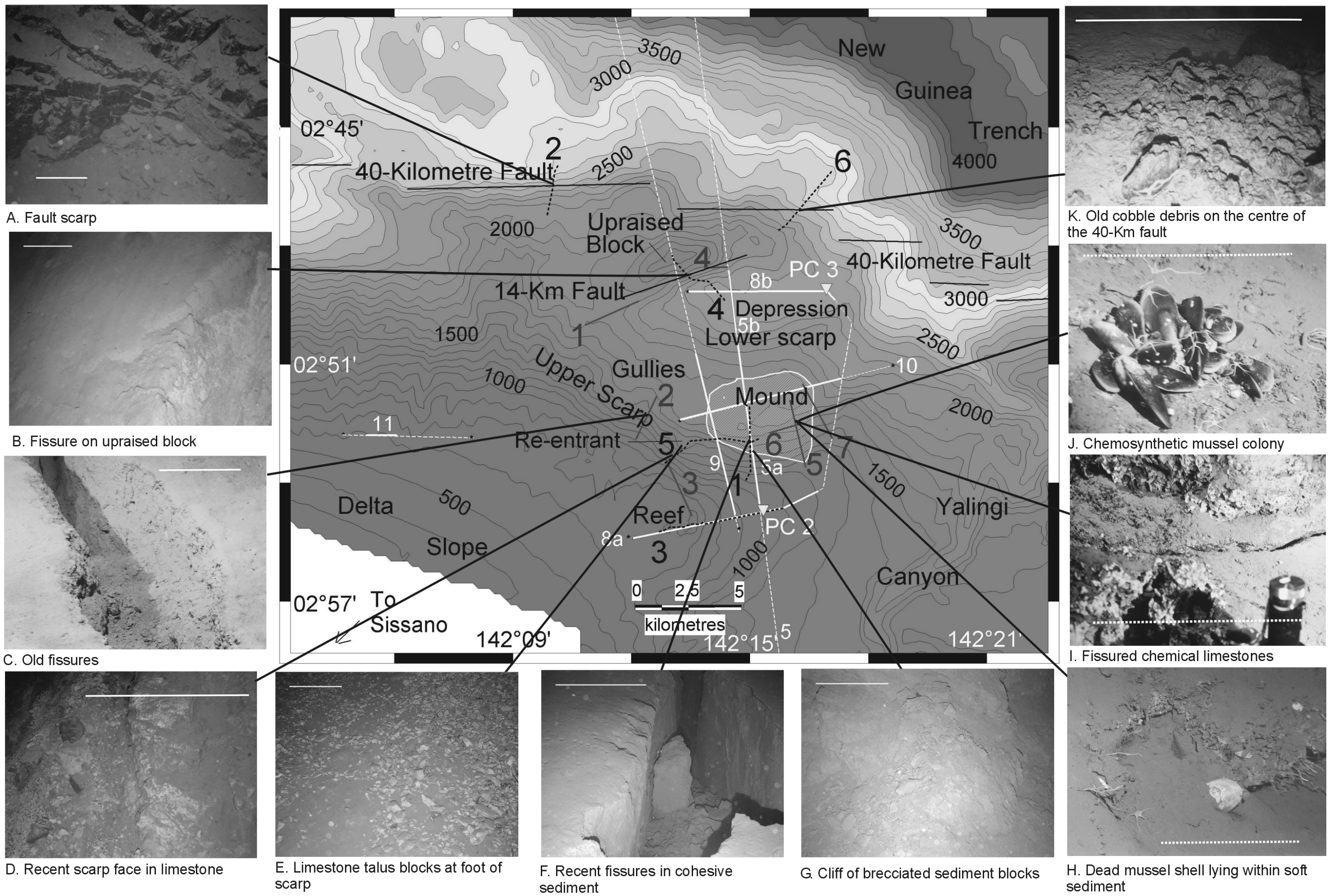

Figure 2: Ampitheater area off Sissano Lagoon (for location see Fig. 1) showing main morphologic features and photographs of significant seabed features (Scales: solid white line is 1 m, dotted white line is 0.5 m). Solid black lines are faults; hachured area defines the slump area of July 1998; dashed white lines are ROV traverses; solid white lines are MS traverses; white filled triangles are sediment core locations.

is V-shaped. The trench to the west of 142.66°E becomes NW–SE trending, is wider and planar floored; maximum water depth is 4200 m. The Pacific Plate comprises the New Bismarck Sea Plate in the east and the Caroline Plate to the west. Their boundary is indistinct and interpreted to lie along an arcuate line of seamounts. The New Bismarck Sea Plate is characterized by shallow water and in the south crests at 1400 m: it appears to "intrude" into the Caroline Plate.

3. Sub-bottom Profiles and Sediment Cores

Sub-bottom profiles (SBPs) were acquired mainly off of Sissano Lagoon and Aitape in the area of the amphitheater and the Yalingi Canyon (Figs. 1 and 2). Four sediment piston cores were also acquired (Figs. 1 and 2). On the steep gradients of the inner trench slope there is very limited SBP penetration and data quality is poor. The headwall of the amphitheater is irregular with steep scarps interpreted as rotational faults interrupted by benches of shallow gradient. At the foot of the reef the seabed sediment was sampled in Core PC 2 where 8.27 m of homogeneous, cohesive clays were recovered. In depressions at the base of the amphitheater, in the inner slope basins and in the New Guinea Trench SBP penetration is up to 40 m and the records show internal seismic stratification. Sediment cores in these depressions comprise inter-bedded soft hemipelagic mud and fine sand and coarse silt turbidites.

4. Seabed Observations

Six remotely operated vehicle (ROV) and seven manned submersible (MS) transects were carried out in the area of the amphitheater (Fig. 2). Of these transects, seven traversed the amphitheater upper scarp and three the southern margin of the upraised block. There was one transect across the reef and two across the 40-km fault: one in the east and one in west.

4.1 Amphitheater upper scarp

In the west on MS Dive 2, the seabed sediment comprised cohesive olive-green clays with steep dips. At the start of the dive there were displaced blocks and at 1190 m there were numerous fissures, tens of meters long, ~50 cm deep and up to 1 m wide (Fig. 2c). All exposed sediment surfaces are degraded.

In the central area the two ROV traverses (1 and 5) revealed the Upper Scarp to comprise a steep slope interrupted by shallow benches. On the bench between 1250 and 1550 m there are prominent east-west trending fissures formed in cohesive clay (Fig. 2f). The fissures are over 50 m long, 1 m wide, and over 3 m deep (Fig. 2f). Fissure margins are sharp and vertical. An almost vertical cliff, 10–15 m high at 1500 m, comprises brecciated cohesive sediment (Fig. 2g). Sediment at some locations is sulfide rich and associated with white bacterial mats and rare tubeworms. ROV Dive 2 traversed a re-entrant in the headwall, the southern wall of which formed an almost vertical limestone cliff with little sediment cover (Fig. 2d). Below the cliff, the re-entrant floor is covered with angular blocks of limestone (Fig. 2e).

In the east of the upper scarp the three MS dives (5, 6, and 7) traversed a variety of seabed features. The seabed on the mound is undulating, with fissures in the cohesive sediment. At the foot of the upper scarp there are slipped dm-sized angular blocks of cohesive sediment. The lower scarp between 1677 m and 1621 m is steep (50°) and extensively disturbed by fluid expulsion. In the cohesive sediment there are fissures and slumps with slipped sediment blocks. Fissures have vertical sides and are hundreds of meters long, meters wide, and meters deep. They are not eroded. Within the sediment there is limestone (Fig. 2i) comprised of dm thick tabular blocks. Some blocks are in situ, but most are slipped (Figs. 2h and i). The seabed sediment is commonly black with sulfides and white with bacterial mats and tubeworms. There are numerous chemosynthetic communities of mussels, *Calyptogena* sp, tubeworms, and starfish (Fig. 2j). Active fluid expulsion was observed. Above 1600 m the seabed gradient is less steep (∼20°) and the seabed mainly featureless apart from minor steeper scarps where there is small-scale slumping with dislodged cohesive sediment blocks. At the top of the upper scarp (above 1227 m) the gradient increases and there are arcuate slumps. On the surface of the slumps are slipped angular blocks of cohesive sediment. Above the slumps there are a series of en echelon fissures that evidence downslope slip. The seabed of the upper scarp on MS Dive 7 was featureless.

4.2 40-km fault, upraised block, and reef

The traverses across the 40-km fault showed minor movement in the west (ROV Dive 2, Fig. 2a) and no activity at all in the center (Dive 6, Fig. 2k). The ROV (Dive 4) and MS (Dive 4) across the southern margin of the upraised block showed recent activity in the form of steep fresh scarps (Fig. 2b) and chemosynthetic biotas, but the length of the fault involved was limited to less than 1 km. ROV Dive 3 on the reef proved this feature to be formed at intertidal depths and thus subsided to present depths of 500 m.

5. Interpretations: Regional Framework

The new data shows the area offshore of northern PNG to be undergoing active failure and subsidence by tectonic erosion along the base of the inner wall of the New Guinea Trench. Subsidence extends to shallow water depths (as shown by the reef at 500 m) and onshore. The Sissano Lagoon subsided in 1907 (Neuhauss, 1911). However, the processes of failure and erosion appear to vary along the margin. In the east, there is intensive erosion and collapse along the base of the inner trench wall by strike-slip deformation. In the west, deformation is predominantly dip-slip and the wider inner trench wall, with back-tilted lower-slope basins, suggests a more extensional style of deformation. Along-strike variation in morphology is attributed to oblique convergence at the New Guinea Trench, in combination with an east-west variation in structure and morphology of the down-going plate (Tappin *et al.*, 2001).

6. Interpretations: Transition Zone off Sissano Lagoon

The change in the morphology and style of deformation along the inner trench wall takes place just offshore of Sissano. Thus the transition-type morphology described in the Sissano area appears to be due to the location and effects of the change in the type of plate subducted. Offshore of Sissano there is active subsidence by normal faulting and sediment slumps that form amphitheater shaped features. The slumps may be nucleating along normal faults in the slump headwalls and both younger and older events have been identified. The amphitheater has formed over several slump events. The most youthful of these is in the east (Fig. 2). A multichannel seismic line over the eastern part of the amphitheater imaged a sediment slump 5 km long from head to toe and a maximum of 740 m thick (Sweet and Silver, 2001).

7. Interpretations: Sediment Types in the Area

The sediment in the cores from amphitheater is cohesive clay and stiff clays are more likely to cause tsunamigenic mass failure than soft sediment in translational failures (Turner and Schuster, 1996). Offshore of PNG sedimentation rates on the inner trench wall are low as shown by the extensive presence of canyons on the steeper slopes. The sediment sampled in Core PC 2 and in the sediment cores from the ROV, together with the limited penetration on the SBPs, suggests that on these slopes the sediment is homogeneous, stiff, and cohesive.

8. Interpretations: Ages of Slumps and Faults—the Tsunami Mechanism

The visual evidence shows the area off Sissano lagoon to have been subject to recent seabed shaking. This shaking was probably the result of the earthquake and aftershocks of July 1998. Modeling of the 1998 tsunami shows that a reverse fault (overthrust to the south) of 40 km is required to produce the tsunami wave measured. Of the faults investigated, the 40-km fault is normal and is active only along its western segment. The 14-km fault is also active, however the fault is too short and the throw measured too small to create the tsunami.

The upper scarp of the amphitheater showed evidence of recent seabed movement with a concentration of activity in the east. Degraded seabed features in the west show slumping here not to be of recent date. The sharply defined fissures in the east are of more recent formation. They increase in number toward the east in which direction there is also an increase in the abundance of the chemosynthetic biotas together with active fluid expulsion. Thus we conclude the most recent seabed movement to be in the east. A simulation of a slump in the east with an assumed volume of 6 km^3 produced the run-up measured onshore (Tappin *et al.*, 2001).

9. Conclusions

From the offshore data acquired, the most likely source of the July 1998 tsunami that struck northern PNG is a sediment slump located 25 km offshore of the Sissano Lagoon in the eastern part of the amphitheater. The slump area is approximately 5×5 km with a maximum of 740 m thickness. Failure was in cohesive clays, with a rotational failure mechanism. There is no evidence on the data acquired for a steeply dipping reverse thrust. The shallow water area off of Sissano bounded by the deep Yalingi canyon in the east probably increased the tsunami height by focusing the wave onto the Sissano Lagoon.

Acknowledgments. The authors wish to thank JAMSTEC and SOPAC for their support. DRT publishes with the permission of the British Geological Survey, Natural Environment Research Council, United Kingdom.

10. References

Davies, H.L. (1998): *The Sissano Tsunami 1998*. University of Papua New Guinea Printery, Port Moresby.

Kawata, Y., B.C. Benson, J.L. Borrero, H.L. Davies, W.P. de Lange, F. Imamura, H. Letz, J. Nott, and C.E. Synolakis (1999): Tsunami in Papua New Guinea was as intense as first thought. *Eos Trans. AGU*, *80*(9), 101, 104–105.

Matsuyama, M., J.-P. Walsh, and H. Yeh (1999): The effect of bathymetry on tsunami characteristics at Sissano Lagoon, Papua New Guinea. *Geophys. Res. Lett.*, *26*, 3513–3516.

Neuhauss, R. (1911): *Deutsch Neu-Guinea*. Band 1, 22–27. Verlag Dietrich Reimer (Ernst Vohson) Berlin.

Sweet, S., and E.A. Silver (2001): Seismic reflection images of the source region of the 1998 Papua New Guinea tsunami. In *Prediction of Underwater Slide and Slump Hazards*, edited by P. Watts, C.E. Synolakis, and J.-P. Bardet, Balkema, Rotterdam, Netherlands.

Tappin, D.R., T. Matsumoto, and shipboard party (1999): Offshore surveys identify sediment slump as likely cause of devastating Papua New Guinea tsunami 1998. *Eos Trans. AGU*, *80*(30), 329, 334, 340.

Tappin, D.R., P. Watts, G.M. McMurtry, Y. Lafoy, and T. Matsumoto (2001): The Sissano, Papua New Guinea tsunami of July 1998—Offshore evidence on the source mechanism. *Mar. Geol.*

Turner, A.K., and R.L. Schuster (1996): Landslides: Investigation and mitigation. Special Report 247. Trans. Res. Board, National Academy Press, Washington, D.C.