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Subducted, detached, and torn slabs beneath the Greater Caucasus

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ABSTRACT

The Greater Caucasus Mountains contain the highest peaks in Europe and define, for over 850 km along strike, the leading edge of the second-largest active collisional orogen on Earth. However, the mechanisms by which this range is being constructed remain disputed. Using a new database of earthquake records from local networks in Georgia, Russia, and Azerbaijan, together with previously published hypocenter locations, we show that the central and eastern Greater Caucasus Mountains are underlain by a northeast-dipping zone of mantle seismicity that we interpret as a subducted slab. Beneath the central Greater Caucasus (east of 45°E), the zone of seismicity extends to a depth of at least 158 km with a dip of ~40°NE and a slab length of ~130–280 km. In contrast, beneath the western GC (west of 45°E) there is a pronounced lack of events below ~50 km, which we infer to reflect slab breakoff and detachment. We also observe a gap in intermediate-depth seismicity (45–75 km) at the western end of the subducted slab beneath the central Greater Caucasus, which we interpret as an eastward-propagating tear. This tear coincides with a region of minimum horizontal convergence rates between the Lesser and Greater Caucasus, as expected in a region of active slab breakoff. Active subduction beneath the eastern Greater Caucasus presents a potentially larger seismic hazard than previously recognized and may explain historical records of large magnitude (M 8) seismicity in this region.

1. Introduction

The Greater Caucasus Mountains are located between the Black and Caspian Seas, ~500 km north of the main Arabia–Eurasia plate boundary, and are presently the main locus of active NE–SW directed plate convergence in this central portion of the collision (Fig. 1; e.g., [52,4,94]). Potential earthquake sources are often obscure in such intracontinental regions, due to their distance from plate boundaries [31]. Instrumentally measured earthquakes in the Greater Caucasus region are generally modest ($M_w < 6$, [93,53,29,107]), with the largest recorded earthquake being the M_w 6.9 1991 Racha event along the southwestern flank of the range (Fig. 1; [108,39,107]). However, historical records in the region extend back to ~2000 B.C. (e.g., [61,101]) and suggest numerous larger earthquakes (e.g., [17,88,61,14,25,47,101]). These include an event in 1668 centered near Sheki, Azerbaijan that may have exceeded M 8 and that completely destroyed the city of Shemakha, killing ~80,000 people (e.g., [88]).

An essential prerequisite for identifying potential seismic sources and characterizing earthquake hazard is to establish the tectonic context and lithospheric architecture of the Caucasus region. However, the first order structural architecture of the range is not yet well constrained. A particularly contentious question is whether or not subduction or significant crustal underthrusting occurred during Cenozoic formation of the Greater Caucasus (e.g., [98,83]). The existence and nature of a Cenozoic subduction zone along the southern margin of the Greater Caucasus has been debated for decades (cf. [17,92,41,33,98]). However, renewed support for the presence of a north-dipping subduction zone has been provided by modeling of GPS velocity fields [110,94], confirmation by Mellors et al. [80] of the depth of an earthquake at 158 ± 4 km beneath the eastern Greater Caucasus, and

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documentation by Skolbeltsyn et al. [103] of a high-velocity shear wave anomaly extending to a depth of ~250 km in the region of this deep event.

Here we build upon the work of Mellors et al. [80] and Skolbeltsyn et al. [103] by providing the first clear images of a subducted slab beneath the central and eastern Greater Caucasus using a newly assembled database of earthquake hypocenter locations. We compiled this database using recent (2005–2013) records from local digital networks in Georgia, Russia, and Azerbaijan, augmented with a small number of previously reported sub-crustal events. Using immersive data visualization tools we identified the three-dimensional structure of the earthquake cloud and established its spatial correlation with surface topography, GPS velocities and significant historical earthquakes. Confirmation of the existence of a subduction zone beneath the eastern Greater Caucasus suggests the potential for destructive future earthquakes, substantially larger than those recorded instrumentally (e.g., [29,53,93,107]).

2. Debated structure of the Greater Caucasus

The Greater Caucasus Mountains formed from Cenozoic closure of a Jurassic-Cretaceous back-arc basin, referred to here as the Greater Caucasus Basin, that originally opened north of the Jurassic and Cretaceous-aged Lesser Caucasus arc during north-dipping subduction of Neotethys (e.g., [2,40,120]). Recent thermochronologic work indicates that initial slow growth of topography began in the western Greater Caucasus during the Oligocene [114,113] and that rapid exhumation of the range started nearly synchronously along-strike at ~5 Ma [7,8], coincident with a tectonic reorganization of the entire Arabia-Eurasia collision zone [116,79,4]. In contrast to these well-defined timing constraints, the original width of the back-arc basin, the extent to which basin closure was accommodated by subduction, and total magnitudes of Cenozoic shortening within the Greater Caucasus all remain poorly known (e.g., [1,11,12,26,33]).

Subduction beneath the Greater Caucasus has been either explicitly argued for, or indirectly supported by observations of sub-crustal earthquakes beneath the Greater Caucasus, beginning with Soviet-era studies of travel-time locations and waveform analysis of events recorded in local network data [71,100,43,109,44]. Both Khalilov et al. [58] and Khain and Lobkovskiy [57] argued for subduction, in part based on these early earthquake data. More recently, Mellors et al. [80] used available waveform data for local and regional events recorded between 2005 and 2009 to confirm depths for sub-crustal events reported in two earlier catalogs of teleseismic data [29,30,84]. In particular, Mellors et al. [80] provided a detailed analysis of the deepest event in the catalogs, which occurred on October 12, 2006 beneath the northern foothills of the Greater Caucasus, at a relocated depth of 158 ± 4 km, and established its sub-crustal nature. Mellors et al. [80] concluded that the few sub-crustal events seen in the global catalogs suggested northeast-dipping subduction beneath the Greater Caucasus, most probably of oceanic crust along the northern edge of the Kura Basin. Most recently, Skolbeltsyn et al. [103] used event-based Rayleigh wave tomography to document a positive S wave velocity anomaly beneath the eastern part of the Greater Caucasus and the Kura Basin that extends to depths of ~250 km, which they interpreted as resulting from underthrusting or subduction of Kura Basin lithosphere under the Greater Caucasus. Earlier tomographic studies [63,76] imaged a similar high-velocity body under the eastern Greater Caucasus extending to a depth of at least 150 km, but less than 250 km, although neither study inferred subduction in this area. Pull from a subducted slab beneath the Greater Caucasus is inferred from GPS velocities that indicate both eastward-increasing convergence rates within the Greater Caucasus and counter-clockwise rotation of the Kura Basin [94]. Vernant and Chéry [110] likewise argued for slab pull based on geodynamic modeling of the GPS velocities. Finally, earthquakes beneath the Apsheron Sill and subsidence modeling in the South Caspian Basin indicate that the oceanic crust of the South Caspian has begun subducting beneath the southern margin of the Middle Caspian Basin to the east and along-strike of the former Greater Caucasus Basin (e.g., [85,86,95,77,5,18,93,53]).

However, subduction beneath the Greater Caucasus remains debated. The accuracy of earthquake depths and locations in Soviet-era studies has been challenged for some time (e.g., [28]) and earthquake catalogs that are based on teleseismic data show few events with depths more than ~20 km beneath the range (e.g., [29,107,80]). Koulakov et al. [63] interpret the high-velocity zone under the eastern Greater Caucasus imaged in their tomographic model as reflecting delamination, rather than subduction. In contrast to other tomographic studies [63,76,103], the teleseismic P wave tomographic model of Zor [121] shows a *low* velocity zone to a depth of ~200 km under the region of previously reported deep earthquakes (his L2 anomaly), which is also interpreted to result from delamination. A lack of geologic signatures of subduction, including the apparent absence of an ophiolitic suture, a volcanic arc, an accretionary complex, or exposures of blueschist or high-grade metamorphic rocks is also cited as evidence against subduction being active during formation of the Greater Caucasus (e.g., [98,83]). Instead, structural models without a subduction component have typically accommodated convergence in the Greater Caucasus by crustal thickening (e.g., [32,53,4]). Finally, it is not clear that the nascent subduction zone along the Apsheron Sill should be expected to continue westwards into the Greater Caucasus, due to differences in crustal structure along strike (e.g., [53,6,56,103]).

3. Data and methods

3.1. New composite catalog of earthquake locations

A fundamental problem in studying seismicity within the Caucasus region is the lack of a comprehensive earthquake catalog for this region, which straddles the countries of Georgia, Azerbaijan, Russia, Armenia, and Turkey, each with an independently maintained seismic network and database. Ultimately, a systematic and self-consistent reassessment of the earthquake data is necessary to fully constrain the crustal structure of the Greater Caucasus region. However, the required primary data needed for such an exercise are not generally publicly available and will require extensive effort to compile considering geopolitical relations in the region. Despite this problem, rich, publicly available catalogs of earthquake locations exist for the Caucasus region. The present study provides an intermediate step by compiling and visualizing existing catalog data to both help motivate such comprehensive work and investigate possible subduction beneath the Greater Caucasus. Specifically, we combine records from 7 sources to assemble a composite catalog of 3348 earthquake hypocenter locations. Metadata for each source are listed in Table S1, including the spatial, temporal, and minimum-magnitude criteria used to filter the primary catalogs. The composite catalog is provided in Table S2 (Appendix A). Duplicate events were removed according to hypocenter location, as explained in the supplement. We discuss the details of these individual catalogs and the caveats of the composite catalog below.

The core of the composite catalog comprises 3275 recent events (2005–2013) reported by the European-Mediterranean Seismological Center (Catalog #0, $N = 1579$ events) and those determined using local digital networks in Georgia (Catalog #1, $N = 564$), Russia (Catalog #2, $N = 876$) and Azerbaijan (Catalog #3, $N = 256$).