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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.

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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., [52,494]). 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 Skolbel'syn 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 Skolbel'syn 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, Skolbel'syn 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, $N = 256$).

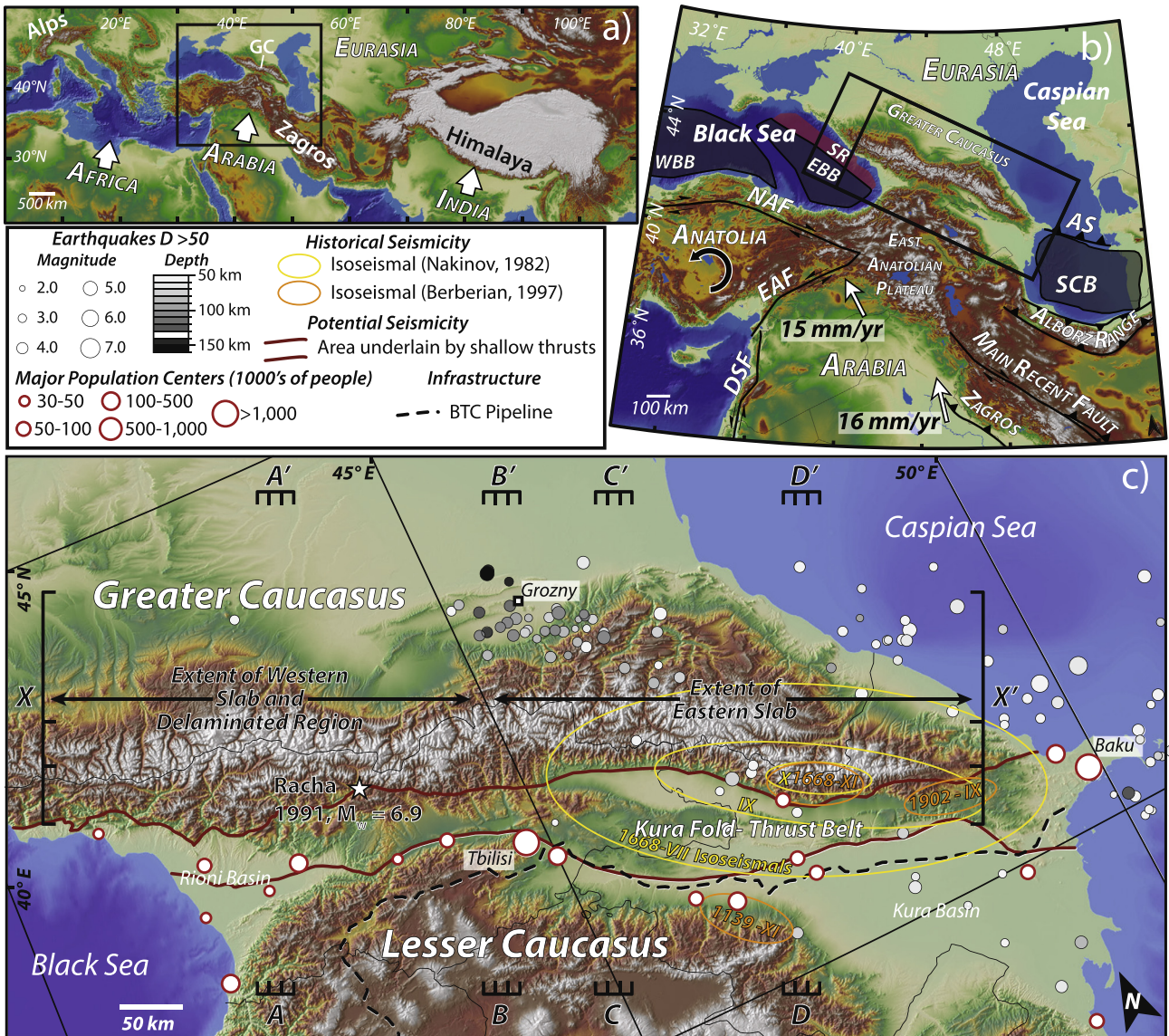


Fig. 1. (a) Location of Arabia–Eurasia collision zone within the Alpine–Himalayan belt. GC = Greater Caucasus. Box outlines bounds of Fig. 1b. (b) First-order structures within the Arabia–Eurasia collision zone. Dark gray zones in Black and Caspian seas indicate location of oceanic crust beneath the South Caspian Basin (SCB, [102]) and Eastern and Western Black Sea Basins (EBB and WBB, [87]). The red zone in the Black Sea is Shatsky Ridge (SR, [87]). Arrows indicate motion of Arabia relative to stable Eurasia from the REVEL 2000 velocity model [99]. Smaller black box outlines bounds of Fig. 1c. and larger box outlines Fig. 4b. Abbreviations are as follows: NAF = North Anatolian Fault, EAF = East Anatolian Fault, DSF = Dead Sea Fault, AS = Apsheron Sill. (c) Greater and Lesser Caucasus region with main physiographic features labeled, along with major population centers and infrastructure. Circles with black outlines are earthquakes discussed in this work with depths greater than 50 km with their size scaled by magnitude and colored by depth. Locations and sizes of isoseismals for events with magnitudes greater than 9 in the Caucasus regions [88,14]. The black brackets indicate the positions of the profiles shown in Fig. 2. Note that the wide part of the brackets indicate the width of the earthquake swath and the thinner, inset bracket indicates the width of the associated topographic swath. Base maps for all figures are shaded relief maps derived from SRTM 90 meter resolution data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The Georgian catalog used here is the publicly available subset of an unpublished catalog containing 3629 events that is currently being analyzed [48]. Records from catalogs #0 through #3 were obtained from publicly available websites listed in Table S1 and contain 103 events with depths ≥ 50 km. To further characterize deep seismicity, the composite catalog also contains 73 older sub-crustal events from three sources: a reanalysis of teleseismic data (Catalog #4, $N = 8$, depth ≥ 40 km, $Y = 1968$ –2006; [80]), a compilation of events from Soviet-era bulletins and papers (Catalog #5, $N = 27$, depth ≥ 50 km, $Y = 1965$ –1996; [45]), and events observed by a Soviet-era local network in Georgia and cataloged in an unpublished database by the Institute of Geophysics at Tbilisi State University (Catalog #6, $N = 38$, depth ≥ 50 km, $Y = 1961$ –2004).

Locations of events reported by the European-Mediterranean Seismological Center (Catalog #0) were determined using both local and teleseismic arrival times (station code, phase picking, calibrated amplitude/period) and source parameters (origin time, epicenter coordinates, hypocentral depth, magnitude) from 65 contributing networks, including those in Georgia, Russia, and Azerbaijan. Events in the Georgian catalog (#1) were located by the Seismic Monitoring Center (SMC) at Ilia State University using HYPO71 [72,73] and data from the digital seismic network of Georgia plus data from stations in Russia, Armenia, Azerbaijan, and Turkey. Data from outside Georgia are provided as arrival picks, rather than primary waveforms. The catalogs of the Russian Academy of Sciences (Catalog #2) and the Republican Seismic Survey of the

Azerbaijan National Academy of Sciences (Catalog #3) report neither the methods by which events were located nor location uncertainties, although we believe HYPO71 is being used. Events reported by Mellors et al. [80] (Catalog #4) were located by reanalysis of primary waveform data, and those compiled by Godzikovskaya [45] (Catalog #5) were obtained from 31 different Soviet-era earthquake catalogs and research papers as detailed in the Russian version of Godzikovskaya [45]. The method used to calculate locations is unknown for events reported by the Institute of Geophysics (Catalog #6). Data in the composite catalog are presented in a variety of magnitude scales, based on the different scales within the original catalogs. Relationships between local and moment magnitude scales do not appear to have been established for this area, as has been done elsewhere (e.g., [96]).

Uncertainties in event locations are generally unavailable in the original sources from which the composite catalog was compiled. To assess such uncertainties, we conducted three analyses. First, we evaluated uncertainties determined using HYPO71 and reported in an unpublished (and not yet publicly available) database of events maintained by the SMC. The distribution of horizontal and vertical uncertainties is shown in Figure S1 for the 505 events within Catalog #1 for which we have uncertainty information. The uncertainty values themselves are part of the as yet unpublished, full catalog from which Catalog #1 is derived. Average horizontal and vertical uncertainties are 2.00 ± 1.47 km and 2.21 ± 1.42 km ($\pm 1\sigma$), respectively. Second, Table S3 compares locations for 23 events reported by all four recent catalogs (#0–3). The standard errors for each set of 4 independent depth determinations range from a minimum of 0.3 km to a maximum of 17.1 km. Third, to check locations of older events in Catalog #5, we searched for arrival time information in Georgian records of the 27 events in our catalog, which yielded information for 9 events, 3 of which had sufficient information to recalculate hypocenters. All 3 events remain at subcrustal depths, with differences in depth of 13.6 to 18.4 km between the original (Catalog #5) and recalculated locations (Tables S2 and S4).

Because primary waveform data and arrival times are not publicly available for any of the catalogs we employ, we are unable to relocate events using refined arrival times or a method such as double differencing (e.g., [115]). Thus, we also lack the information needed to quantitatively evaluate epistemic uncertainties that may exist in the primary catalogs, such as biases introduced by location procedures, network coverage, or a priori model assumptions such as Earth structure. All of these are important considerations, but represent future work beyond the scope of this study. Our goal here is to provide an intermediate step to such investigations by exploring the extent to which the existing catalogs reveal lithospheric structure and thereby motivate future efforts to develop a comprehensive catalog of relocated events for this region.

3.2. Visualization and analysis of earthquake hypocenters

To analyze the database, we examined hypocenter locations using standard 2-D profiles (Figs. 1, 2, S3 and S4) and free, open-source software developed by the W.M. Keck Center for Open Visualization in the Earth Sciences (KeckCAVES, <http://www.keckcaves.org>) running on both a desktop computer and in a CAVE immersive visualization environment (Fig. S5 and Movie S1). As explained elsewhere [23], use of this software in a CAVE generates the experience of spatial presence, where users believe they are physically located within a virtual environment (e.g., within the earth) rather than in their true physical location (e.g., in a laboratory; [75,51,82,106,117]).

Specifically, we used the KeckCAVES application Crusta [15] running in a CAVE and on a desktop computer to visualize three-dimensional structure within the cloud of earthquakes and

correlate these structures with topography. Crusta is an interactive virtual globe that renders in real time digital elevation and image data with both high-resolution (e.g., meter/pixel) and large coverage (e.g., whole-Earth).

4. Results: distribution of deep earthquakes

Similar to previous work (e.g., [80]), we consider any earthquake deeper than 50 km to be sub-crustal. This cut-off comes from estimates of average crustal thickness of 45–50 km in the Greater Caucasus region derived from results of deep seismic soundings [62], receiver functions and surface wave studies [46], and upper mantle P-wave tomography [121]. Although most earthquakes within the Greater Caucasus are restricted to the crust (depths <50 km), east of 45°E there are numerous events deeper than 50 km, with some >150 km (Figs. 1, 2, S3, S4, S5 and Movie S1; e.g., [80]). Between 45°E and 47°E, these deep earthquakes define a northeast dipping plane of seismicity that is located along the northern boundary of the Greater Caucasus (Figs. 2, S5 and Movie S1). The western boundary of this zone of deep earthquakes is nearly coincident with the location of the proposed Borjomi-Kazbegi fault (Fig. 4; e.g., [58,92,60]). West of the proposed Borjomi-Kazbegi fault and 45°E there is a marked absence of earthquakes deeper than 50 km, which we attribute to a true lack of deep events because the densest coverage of seismic stations is within this portion of the range in Georgia.

The northeast-dipping plane of seismicity has an apparent dip of $\sim 40^\circ$ and a maximum depth that decreases eastwards (Figs. 2, S5 and Movie S1). At the western end of the zone of seismicity, there is a discontinuity in seismicity down dip, with a lack of ~ 50 km deep events (see profiles B–B' and X–X' in Fig. 2). While there are other partial gaps in seismicity, this is the largest continuous aseismic region in the dipping zone of seismicity, continuing for ~ 100 km along strike (X–X' in Fig. 2) and up to ~ 50 km down dip (B–B' and X–X' in Fig. 2). As with the maximum earthquake depths, the width of the discontinuity also decreases eastwards (from position 350 to 450 km on profile X–X' in Fig. 2) until the zone of deep earthquakes eventually merges with those in the crust. The along-strike extent of the gap between mantle and crustal earthquakes coincides with a zone of minimum convergence velocity identified in GPS measurements (Fig. 2; e.g., [94]).

East of 47°E there are not many earthquakes deeper than 50 km within the Greater Caucasus region, except for a small group between 48.5°E and 49°E with maximum depths of ~ 70 km. However, it is important to note that seismic-network coverage is sparse in this region; thus, it is unclear if the lack of deep events is real or the result of incomplete detection (see Appendix A). Moving eastwards and offshore, into the middle Caspian Basin, deep earthquakes are again present, including those with depths >100 km, and loosely define a north-dipping zone of seismicity similar to findings of previous studies (e.g. Fig. S4; [93,53,5]).

5. Discussion: interpreted Greater Caucasus structure and evolution

5.1. Subduction zone geometry

The most significant feature in the earthquake data is the clear northeast-dipping zone of hypocenters extending into the mantle east of 45°E. We interpret this zone of seismicity as a subducted slab beneath the central and eastern Greater Caucasus, a conclusion also drawn by Khalilov et al. [58] on the basis of fewer events. This slab is most simply explained as a remnant of the former Greater Caucasus Basin (e.g., [2,40,120]) that was subducted during late Cenozoic basin closure leading to formation of the Greater Caucasus. The

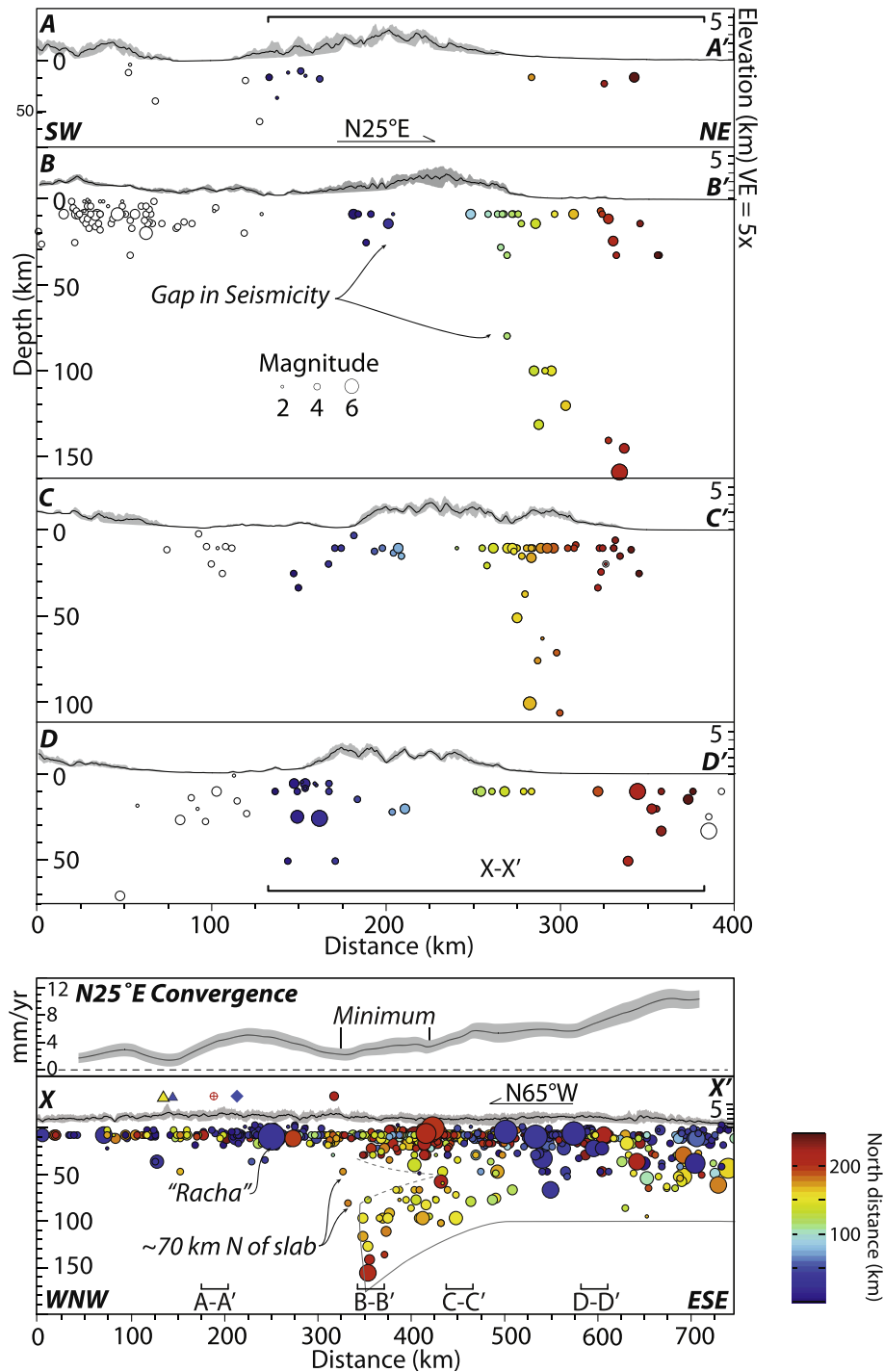


Fig. 2. Swath profiles of earthquake hypocenters and topography; refer to Fig. 1c for profile locations. Profiles A–A', B–B', C–C', and D–D' are oriented N25°E and share the same horizontal scale. The vertical scale is the same for these four profiles, but the maximum depth displayed differs. Profile X–X' is oriented N65°W and is at a different scale than the four NE–SW profiles. Circles indicate earthquake hypocenters and are scaled by magnitude (the same across all five profiles). Earthquakes in white within the NE–SW profiles fall outside the bounds of profile X–X' and dark red at the northern boundary. This color scheme is employed to aid visualization of the NE–SW position of earthquakes in profile X–X'. The earthquake swaths in the NE–SW profiles are 30 km wide and the corresponding topographic swaths are 10 km wide. Topography is virtually exaggerated 5× with the thick black line being the mean topography and the gray bounds corresponding to the minimum and maximum elevations. For profile X–X', the locations of the Greater Caucasus Cenozoic volcanic centers are illustrated above the topography using the same symbols as in Figs. 3 and 4. The calculated convergence above X–X' is calculated by subtracting a linear interpolation of the N25°E components of the Lesser Caucasus GPS station velocities from the Greater Caucasus stations, see Forte [35] or Forte et al. [38] for discussion of this calculation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

presence of such a slab is consistent with previous modeling of GPS data suggesting convergence within the central and eastern Greater Caucasus is partially driven by slab-pull [94,110].

While the slab is clearly imaged by our data in a relatively narrow zone between 45°E and 47°E, understanding the geometry

beyond this region and the relative continuity of the structure is essential for understanding the potential seismic hazard. It is unclear if the absence of a coherent zone of sub-crustal seismicity east of 47°E reflects a true lack of a slab or stems from lower-resolution coverage of areas outside of Georgia, particularly in

the politically volatile areas of Chechnya and Dagestan. Thus, it is also unclear if the slab within the central and eastern Greater Caucasus is continuous with the one beneath the Apsheron Sill identified in previous studies (e.g., [93,53,5]) and imaged by our data (Fig. S5 and Movie S1). Although we suspect that the slab continues eastward and links with the one beneath the Apsheron Sill, more records of local seismicity are needed to determine if the slabs are continuous or if they are separated by the West Caspian Fault (e.g., [53,6,56]). Southeast of the Greater Caucasus, the West Caspian fault separates the Talysh-Vandam zone to the west from the South Caspian Basin to the east [112]. This transition is marked by both a significant increase in sedimentary thickness from west to east across the fault, and the juxtaposition of continental crust of the Talysh-Vandam zone on the west against oceanic-affinity crust to the east [112,13]. The West Caspian Fault has been interpreted as behaving as a transform fault [64], and thus may represent a potential loci of slab segmentation. Unfortunately, addressing such questions is hampered because access to seismic data in the northern Caucasus is difficult, and, due to the location of the Caspian Sea, seismometer locations are not optimal for determining how subduction under the Greater Caucasus relates to that under the Apsheron Sill, nor for providing a strong constraint on the depth and extent of the slab. Fully understanding the nature of this system will depend on the integration of as many datasets as we can assemble, as there is no near future likelihood of improving seismic coverage in these areas.

We infer that the down-dip gap in seismicity in the region with the deepest earthquakes (Profiles B–B' and X–X' on Fig. 2) most likely represents a laterally propagating tear in the slab. The slab appears largely continuous farther to the east in our data (Profile C–C' on Fig. 2), constraining the width of this tear to <100 km along-strike. Such an eastward propagating tear in the slab explains both the local minima in convergence velocity coincident with the location of the tear and the eastward increase in convergence velocity along-strike (Profile X–X' on Fig. 2). Observations from both other orogens and geodynamic models indicate that convergence velocity immediately up-dip of a laterally propagating slab tear will be nearly zero because the remnant portion of the slab no longer feels the negative buoyancy of the deeper slab (e.g., [118]). Along-strike from a slab tear, the up-dip portion of the still-attached slab will exhibit a velocity gradient increasing away from the tip of the slab tear, identical to the pattern observed in the eastern Greater Caucasus (Profile X–X' on Fig. 2).

The asymmetric distribution of deep earthquakes along strike is particularly striking in the dataset, with a lack of sub-crustal events west of 45°E but clear evidence of earthquakes at mantle depths to the east (Fig. 2). Previous studies have noted both this pattern and similar along-strike variations in other aspects of the crustal structure of the Greater Caucasus (e.g., [80,46,97]). Unlike in the eastern part of the range, data coverage within Georgia is dense, therefore, the lack of deep seismicity west of 45°E most likely indicates a true lack of subcrustal seismicity in this region. We interpret the lack of subcrustal seismicity as evidence of recent slab detachment based on both previous reports of anomalously low subsidence in the northwestern foreland of the Greater Caucasus (i.e. subsidence rates in the foreland that are lower than those expected based on simple flexural models and the known volume of the range; e.g., [81,32]) and low upper-mantle seismic velocities west of 47°E in most tomographic models of the range [63,76,103]. These observations led previous workers to hypothesize a component of dynamically driven uplift of the foreland due to a delamination event beneath the western Greater Caucasus [33,121,63]. Here, we suggest that this delamination was the detachment of a subducted slab, as opposed to the removal of a dense crustal root as proposed by Ershov et al. [33] and Koulakov et al. [63]. Numerical models indicate slab detachment can cause significant rock

uplift (e.g., [19]), consistent to a first order with the observation of uplift of the northwestern Greater Caucasus foreland presented by Ershov et al. [33]. Additionally, a tomographic model of the western Arabia-Eurasia collision zone imaged a zone of anomalously fast Pn velocity north of the central Greater Caucasus and near the edge of the modeled domain (e.g., [3]), which we suggest could be the detached slab. The concentration of deep earthquakes in the eastern portion of the Greater Caucasus, especially in the vicinity of Grozny (Fig. 1), could be interpreted in terms of crustal delamination or a drip, however, we do not favor this interpretation because of the consistent northward dip of the seismicity, its continuity for >400 km along strike, tomographic results that indicate crustal thicknesses of ~50km in the eastern Greater Caucasus [121], and the location of the majority of these deep events along the flanks of the range or in the northern foreland, offset >100 km from the high topography of the range. The high topography of the Greater Caucasus has also been explained in terms of “dynamic topography” generated by small-scale mantle flow without subduction [34]. We do not consider this model a robust explanation for the earthquake distributions presented here or the geology of the Greater Caucasus because the small-scale convection model predicts only uplift and no observable surface shortening, which is demonstrably false given the geology of the fringing fold-thrust belts (e.g., [36,37]). In addition this model predicts mantle flow parallel to the strike of the range, perpendicular to observed convergence directions [94]. It is possible that small-scale mantle convection could contribute to the topography of the Greater Caucasus, but if it is acting in this region, it is occurring in concert with shortening driven by subduction processes.

5.2. Arc magmatism?

The absence of an obvious Cenozoic volcanic arc has been used to argue against active subduction beneath the Greater Caucasus (e.g., [98,83]), but this may simply reflect the magnitude, angle, or rate of subduction, or the recency of its initiation. At least five Neogene-Quaternary aged volcanic centers and associated intrusive centers have been identified in the western Greater Caucasus (Figs. 3 and 4), the structure, deposits, and geochemistry of which are all consistent with genesis in an arc setting (Fig. 3 and Supplemental Text; e.g., [74,66,70,69]). These range in age from late Miocene to Quaternary and include active stratovolcanoes (e.g., Elbrus and Kazbek, [66,65]), a caldera (e.g., Chegem, [74,42]), and granitic to dacitic intrusions (e.g., Elbrus, Kazbek, Lelaashka and Pyatigorsk; [67,68,65,70,69]).

Although the geochemistry of silicic lavas in the Greater Caucasus is consistent with genesis in a volcanic arc setting (Fig. 3), their geographic distribution is harder to explain (Fig. 4). Elbrus, Chegem and Kazbek define a trend along-strike within the Greater Caucasus consistent with a volcanic arc developed above a northeast-dipping subduction zone. However, the presence of late Miocene intrusions at Pyatigorsk and Lelaashka, significantly north and south, respectively, of this trend, is somewhat unusual. One possible explanation for the spatial trend of volcanism is small-scale toroidal flow around the edge of the seismically observed slab (e.g., [119,55]) perhaps enhanced by small-scale convection generated across a steep gradient in lithospheric thickness that underlies the Greater Caucasus (e.g., [59,78]). Nonetheless it remains unclear why volcanism appears absent east of ~45°E, where both the earthquake locations presented in this work and elsewhere [80], along with modeling of GPS velocity data [110,94] indicate active subduction. One possibility is that young volcanic centers are present, but have not been identified in the relatively unexplored regions of Chechnya and Dagestan (as perhaps indicated by the 2013 report of a previously unknown Miocene volcanic center in

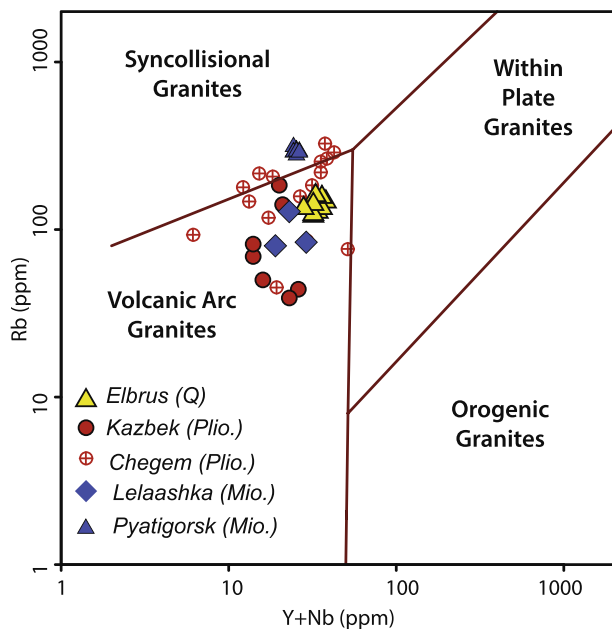


Fig. 3. Tectonic discrimination diagram of igneous rocks [91] in the Greater Caucasus for limited suites of Cenozoic felsic volcanic and intrusive rocks for which trace element isotopic data are available [74,66,65,69]. **Q** – Quaternary, **Plio.** – Pliocene, **Mio.** – Miocene. The majority of samples from all volcanic fields, with the exception of the Pyatigorsk suite, which lies north of the Greater Caucasus near the town of Mineralnye Vody, reveal a volcanic arc-type signature. This signature is common to rocks known to have been associated with modern or past subduction (e.g. the modern and ancestral Cascades; Oligocene magmatism in the Basin and Range, [27,21], but differs from non-arc magmatism (e.g. Yellowstone and the Snake River Plain, [21]. Such a signature suggests a subduction-related origin for much of the Miocene to Recent volcanism in the Greater Caucasus. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Georgia by [69]. Another possibility is that there may not yet have been enough subduction to generate an arc.

5.3. Control on asymmetric detachment

We speculate that the western slab (i.e., portion of former slab west of 45°E) detached in response to attempted subduction of the continental Shatsky Ridge and Dzirula Massif, which may have stalled subduction and led to detachment (Figs. 1 and 4). Attempted subduction of continental lithosphere is commonly cited as driving initiation of slab detachment (e.g., [24,20]). The Shatsky Ridge, which lies mostly offshore along the northeastern boundary of the Black Sea, and the Dzirula Massif, which is interpreted as the onshore continuation of the Shatsky Ridge, are thought to be cored by continental basement and to have formed a single paleo-high that originally divided rift sub-basins within the Black Sea [10], and in particular separated the Eastern Black Sea Basin to the southwest from the former Greater Caucasus Basin to the northeast [87]. While no longer a bathymetric feature within the Black Sea, the buoyancy of the Shatsky Ridge is suggested by its associated strong negative gravity anomaly (–60 mGal free-air, [105]).

We further speculate that the behavior of the eastern Greater Caucasus slab (i.e., portion of slab east of 45°E) was separated from that of the western slab by the Borjomi–Kazbegi (also reported as the Borzhomi–Kasbegi or Northeast Anatolian) fault (Fig. 4), which we interpret to be restricted to the lower plate. The existence and kinematics of this fault have been inferred from earthquake focal mechanisms indicating sinistral strike-slip motion along a NNE–SSW striking zone within the Lesser Caucasus [52] at depths

ranging from 11–33 km [107]. The fault has been extrapolated northwards across the Greater Caucasus, and thus into the upper plate of the subduction zone described here, based on the inference that the fault offsets both the modern topographic crest of the range and the Moho [60,92]. Both the surficial and bedrock geology of the range do not appear to support such upper-plate offset. However, within the lower plate, the fault has been interpreted to behave in a manner akin to a sinistral transform fault, separating the rapidly shortening eastern Caucasus thrust belt from the more slowly deforming western belt [52,92]. Neotectonic studies within the Lesser Caucasus reveal no evidence of active surface deformation associated with this fault [90] and geodetic studies are equivocal, with most interpreting no resolvable motion on the structure (e.g., [94]), although most geodetic networks are not optimally oriented to resolve this question [111]. Recent block models of geodetic velocities in the Middle East prefer a block boundary coincident with the trace of Borjomi–Kazbegi fault, but are insufficient to resolve whether or not the fault is presently active [89]. Thus, a viable interpretation is that the Borjomi–Kazbegi fault may have been a former transform fault in the Greater Caucasus back-arc basin, and that it originally separated the en echelon, east-west striking sub-basins (e.g., [1]), and which now separates the lower plate into eastern and western segments.

The potential slab tear and beginning phases of slab detachment of the eastern Greater Caucasus slab may also be driven by the attempted subduction of more buoyant, continental lithosphere. The location of the tear is largely coincident with an area in which the Greater and Lesser Caucasus appear to be colliding, with a south-verging thrust system from the Greater Caucasus overriding north-verging structures of the Lesser Caucasus (Fig. 1; e.g., [10]).

The timing of detachment of the western slab and the initiation of detachment of the eastern slab are largely unconstrained. Detachment of the western slab likely decreased the convergence velocity in this portion of the range (e.g., [118]), but no detailed structural histories are available for either the foreland fold-thrust belts in the western Greater Caucasus or within the core of the range, without which, identifying the onset of slowing is not possible at this time.

6. Implications for seismic hazard

The presence of a subduction zone along the central and eastern Greater Caucasus significantly impacts the potential seismic hazard throughout the Caucasus region. Active shortening between the Greater and Lesser Caucasus is localized along predominantly south-directed thrusts that sole into a shallow detachment (<10 km deep) beneath the Kura fold-thrust belt that accommodates up to ~15 mm/yr of shortening (Fig. 4, e.g., [36,37,94]). The Kura fold-thrust belt initiated at ~2 Ma [37], but relatively constant and rapid uplift of the main range of the Greater Caucasus since 5 Ma [7,8] suggests that the foreland structures are likely linked to the structures responsible for uplift of the range. The locus of active shortening in the western Greater Caucasus is not as well characterized, in part because rates of shortening across the range are slow (~4 mm/yr; [94]), but available data suggests localization along south verging thrusts in the Rioni Basin, which also are likely structurally linked to deeper thrusts beneath the main range (e.g., [10]). The continued convergence measured geodetically within the western Greater Caucasus [94] indicates that the detachment of the western slab did not shutoff convergence in this region, and thus, while convergence rates are lower in this region (Fig. 4), a significant seismic hazard remains.

While the detailed geometry of the deeper structures beneath the Greater Caucasus remains to be established, modeling of available geodetic and thermochronologic data indicates that the

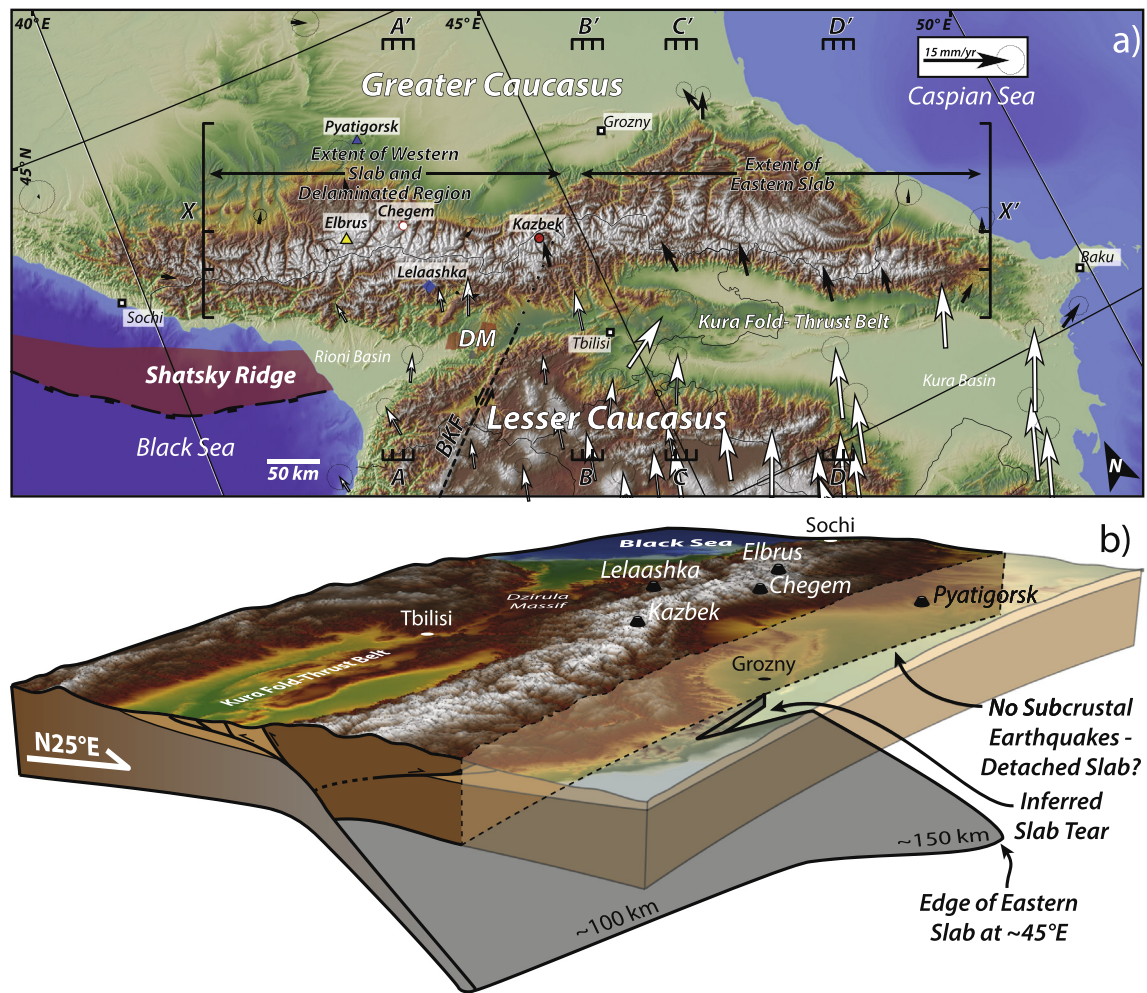


Fig. 4. (a) Major tectonic features of the Greater Caucasus. Arrows are GPS velocity vectors relative to stable Eurasia [94], divided into stations within the Greater Caucasus (black) and Lesser Caucasus and Rioni/Kura Basins (white) similar to Avdeev and Niemi [8]. Colored symbols are locations of Cenozoic volcanic or intrusive centers within the Greater Caucasus, as discussed in the text (not including volcanic centers that are prevalent in the Lesser Caucasus). Symbols are the same as in Fig. 3. Location of Shatsky Ridge from Nikishin et al. [87] and Dzirula Massif (DM) from Banks et al. [10]. Location of Borjomi–Kazbegi Fault (BKF) from [60]. Borjomi–Kazbegi fault dashed where location is approximate within the Lesser Caucasus and dotted where it is shown in the lower plate, beneath the Greater Caucasus. (b) Perspective view, looking southwest, of a simple block model of the Greater Caucasus system. The surface image is taken from the program Crusta, see text for discussion, and is a visualization of SRTM 90 meter digital elevation data over which a shaded relief map, colored by elevation, is draped. Location of cities, physiographic features, and volcanic provinces shown in Fig. 4a and Movie S1 are displayed. Dark brown colors in cross section and the subsurface indicate continental crust and basement, tan colors indicate sedimentary basins, and gray indicates oceanic crust. Along the eastern edge of the block, we illustrate a cartoon version of the structural geometry within the eastern Greater Caucasus with a prominent fold-thrust belt in the Kura foreland basin [36,37] and a south-dipping thrust system on the northern margin of the range [104]. The northern half of the block is semi-transparent to reveal the inferred slab tear and edge of the eastern slab beneath the central Greater Caucasus, roughly below Grozny. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

most parsimonious interpretation is that the Greater Caucasus are underlain by a single, large detachment [9]. This suggests that an earthquake on any of the thrusts along the southern margin of the Greater Caucasus has the potential to rupture a large section of the seismogenic crust, and thus generate a major, or even great, earthquake, similar to those observed in the Himalaya (e.g., [16]). Because of the relative paucity of crustal events in the catalog presented here, the geometry of the crustal portion of the subduction system does not appear to be well constrained. Thus, crucial details, such as the dip of the main detachment beneath the range and potential rupture segmentation remain to be established. Additionally, the extent to which the crustal portions of the subduction system could be described as flat slab or shallow subduction is also unclear, but could have important implications for the degree of coupling across the plate interface, and thus seismic hazard, as well as processes driving surface deformation and mountain building (e.g., [50,49,54]).

Based on the available data, a true assessment of magnitudes of potential earthquakes is not yet possible. However, such work is

critically important because even earthquakes of intermediate magnitude may lead to devastating human impact in this region, as demonstrated by the 1988 M_s 6.8 Spitak earthquake in the Lesser Caucasus, which killed over 25,000 people [22]. Importantly, we note that many of the main population centers and areas of critical infrastructure within the southern Greater Caucasus are underlain by the shallow, north-dipping foreland structures and would likely experience significant shaking during a large magnitude earthquake (Fig. 1). The historical record of seismicity in the southern Greater Caucasus is consistent with this hypothesis, as regions underlain by the eastern Greater Caucasus slab or its up-dip continuation beneath the Kura fold-thrust belt correspond to areas that record large historical earthquakes (Figs. 1 and 4; [14,88]).

7. Conclusions

A new compilation of local earthquake hypocenters yields evidence of a north-dipping subducted slab beneath the eastern

Greater Caucasus Mountains extending to 100–160 km depth. The western Greater Caucasus (west of 45°E) lack sub-crustal earthquakes, but contain volcanic centers consistent with formation in a subduction-related volcanic arc, suggesting that subduction may have occurred along the western Greater Caucasus, but that this slab is now detached. The composite catalog clearly demonstrates the presence of a slab beneath the eastern Greater Caucasus, previously a point of debate for several decades. We attribute the lack of traditional geologic evidence of this subduction event within the Greater Caucasus to the relatively modest amount of subduction. The presence of this subduction zone in the eastern and central Greater Caucasus dramatically affects estimates of seismic hazard in this region, as it presents a mechanism for generating great ($M_w \geq 8$) earthquakes, consistent with events described in the historical record of seismicity (e.g., [88]). Constraint of the seismic hazard in this region will require a more thorough understanding of the structural geometries beneath the southern margin of the Greater Caucasus and the nature of the linkages between the shallow foreland thrusts and deeper structures.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.grj.2014.09.004>. These data include Google maps of the earthquake catalogs described in this article.

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