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Reflection of Seismic Paleoevents in Mesozoic–Cenozoic Terrigenous Sequences of the Northern Caucasus

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Abstract—Numerous traces of paleoseismic events (seismites) were established in Mesozoic–Cenozoic marine sedimentary sequences of the northern Caucasus. These traces are most prominent in the terrigenous Middle Miocene sandy–clayey sediments. Impact of seismic shocks upon the relatively weakly lithified sediments provoked distortion of the primary sedimentary structure, liquefaction of the sandy material, and injections of different morphologies (neptunic dikes and sills). The formation of jointing in sediments fostered their vertical permeability and promoted the migration of diagenetic solutions into the adjacent horizons, which stimulated the formation of subvertical carbonate bodies. The amount and intensity of seismic events varied at different stages of the accumulation of sequences and in different areas of the paleobasin. In the eastern sector of the northern Caucasus, seismic activity similar to the present-day general pattern was likely developed as early as the Middle Miocene: maximum activity in the Dagestan and its westward attenuation. Traces of seismic activity are also recorded in the Maikopian (Oligocene–Lower Miocene) and Lower–Middle Jurassic rocks.

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INTRODUCTION

Deciphering paleoearthquakes is an important and interesting issue in different aspects. First, the analysis of sedimentary sequences and the establishment of intervals with high seismic activity therein provide insight into the tectonic and, in general, geological evolution of a seismoactive region. In addition, earthquakes can affect the processes of lithogenesis, including the generation, migration, and accumulation of liquid and gaseous hydrocarbons. The formation of jointing in rocks can promote their reservoir properties. Study of the consequences of recent seismic events revealed significant variation in the processes of erosion, migration, and input of the sedimentary material (including carbon) into the terminal discharge basins from the earthquake zones, where numerous landslides are formed (Dadson et al., 2003; Hovius et al., 2011; Jin et al., 2016; Malamud et al., 2004; Stallard, 1998; Wang et al., 2015, 2016). Thus, seismic events play an important role in the formation of the Earth's sedimentary cover, primarily in mobile belt zones.

Various aspects of the manifestation of ancient earthquakes in different regions of the world are highlighted in numerous publications, including monographs and thematic collections of papers (Verzilin, 1963, 1979; Garetskii, 1956; *Paleoseismologiya*, 2011; Shrok, 1950; *Ancient Seismites*, 2002; Seilacher, 1969, 1984; Sims, 1973, 1975; and others).

The Greater Caucasus was a region of high seismicity during the whole Mesozoic and Cenozoic history as in the modern epoch. This is suggested by numerous and diverse traces of paleoseismic events recorded in sedimentary sections. Researchers of sedimentary sequences in the Greater Caucasus noted in them signs of different-age earthquakes (Vassoevich and Korotkov, 1935; Gavrilov, 1977; Gerasimov, 1928; Rubinstein, 1949; Tikhomirov and Khain, 1947; and others). In-depth analysis of the state of recent seismicity, manifestation style, and natural aftermaths of earthquakes in the northern Caucasus was accomplished in (Rogozhin et al., 2014).

To designate sediments subjected to the influence of paleoseismic events, term "seismites" was proposed in (Seilacher, 1969). Depending on the lithology of sediments under consideration, researchers engaged in the elucidation of traces of such influence in rock section put into context different meanings, sometimes constraining its application range (Gladkov and Lunina, 2010; Obermeier, 1996; Montenat et al., 2007; and others). In the present paper, this term is used in a general sense and applied to any secondary (postsedimentary) seismogenic bodies.

In Mesozoic–Cenozoic sections, seismites are distributed irregularly – both at different stratigraphic levels and over the entire northern Caucasus. This is caused not only by temporal variations in seismic activity of the region, but also by dissimilar capacity of

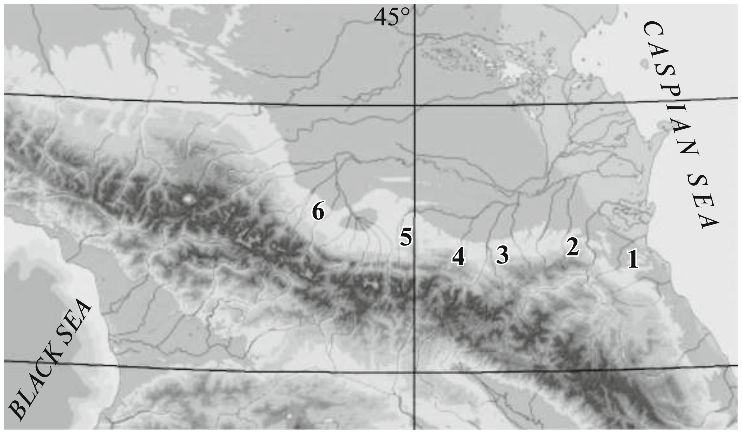

Fig. 1. Fragment of the morphological map of the Greater Caucasus and location of the studied Middle Miocene sections: (1) Buinak Pass; (2–6) along river valleys: (2) Yaryk-su, (3) Elistanzhi, (4) Roshnya, (5) Fortanga, (6) Urukh.

lithologically different sediments to fix traces of seismic events. For example, traces of paleoearthquakes differ considerably in sandy–clayey sediments and clayey–carbonate sediments. The present communication is dedicated to seismites recorded in terrigenous (sandy–clayey and clayey) sequences.

SEISMITES IN THE MIDDLE MIOCENE SANDY–CLAYEY SEDIMENTS OF THE NORTHEASTERN CAUCASUS

One of the stratigraphic intervals with the most prominent manifestation of seismic events is represented by the Middle Miocene (Chokrakian and Karaganian) sequence. Its thickness is as much as 800–1000 m in the Sulak–Assa interfluve area and gradually decreases toward the west. It is mostly composed of sandy–clayey sediments. Thickness of sandstone beds (approximately 10 seams in the Chokrakian section and 13 seams in the Karaganian section) reaches 20 m or more (Vassoevich, 1959; Zhizhchenko, 1940; and others). We studied the Middle Miocene sequence in several sections from Dagestan to North Ossetia. The easternmost section is exposed along the highway across the Buinak Pass (Makhachkala area). In the western areas, we studied sections along valleys of the Sulak, Yaryk-su, Elistanzhi (tributary of the Chanty-Argun River), Roshnya, Fortanga, Suadagdon, and Urukh rivers (Fig. 1).

The greatest number of traces of paleoseismicity (diverse manifestations, different intensities of seismic events, and so on) is recorded in the Buinak Pass section. Here, the Middle Miocene sequence is divided into two large sedimentary cycles. The lower part is dominated by clayey sediments, whereas the upper part is dominated by sandy sediments (Fig. 2). These cycles match approximately two stratigraphic (Chokrakian and Karaganian) subdivisions.

Seismites are irregularly distributed along the Middle Miocene section. After activation of the seismic activity in the terminal Maikopian (end of Early Miocene), the new (Chokrakian) sedimentary basin began to form in a relatively calm setting. At 30–35 m above the Chokrakian basin, we recorded the first prominent seismic complex. The overlying unit in the lower half of the Chokrakian section includes some additional seismic complexes with a spacing of tens of meters.

We believe that the term "seismic complex" should be understood as the whole set of geological bodies closely associated with a specific seismic event or series of events in the course of a relatively small time interval. The most complete seismic complex is observed in the following structures: (1) seismic event horizon (SEH); (2) associated clastic injection bodies – dikes, sills, horizons of reticulated injections, and others; and (3) horizons of detachments and slipping accompanied by the homogenization of rocks, loss of the primary sedimentary bedding, and formation of local low-angle overthrust faults and other distortions in the primary sedimentary structure of sediments.

Seismic event horizons (SEH) represent section intervals (usually 5–7 m thick), where weakly lithified sediments beneath the seawater/sediment interface underwent diverse types of deformation, destruction, and disintegration in the course of paleoearthquakes (Fig. 3). Structures of different SEH can vary notably depending on the lithology (primarily grain size composition) of sediments and degree of their lithification. The internal structure of SEH varies not only in different time intervals, but also within events of a single level.

The lower boundary of SEH can be sufficiently sharp with a distinct transition to the underlying undeformed sediments (Fig. 3a). At the same time, the destructive process occupied a greater thickness of sediments in some places. In this case, the lower boundary of SEH subsided drastically into the underlying beds for 1 to 2 m or more (Fig. 3d).

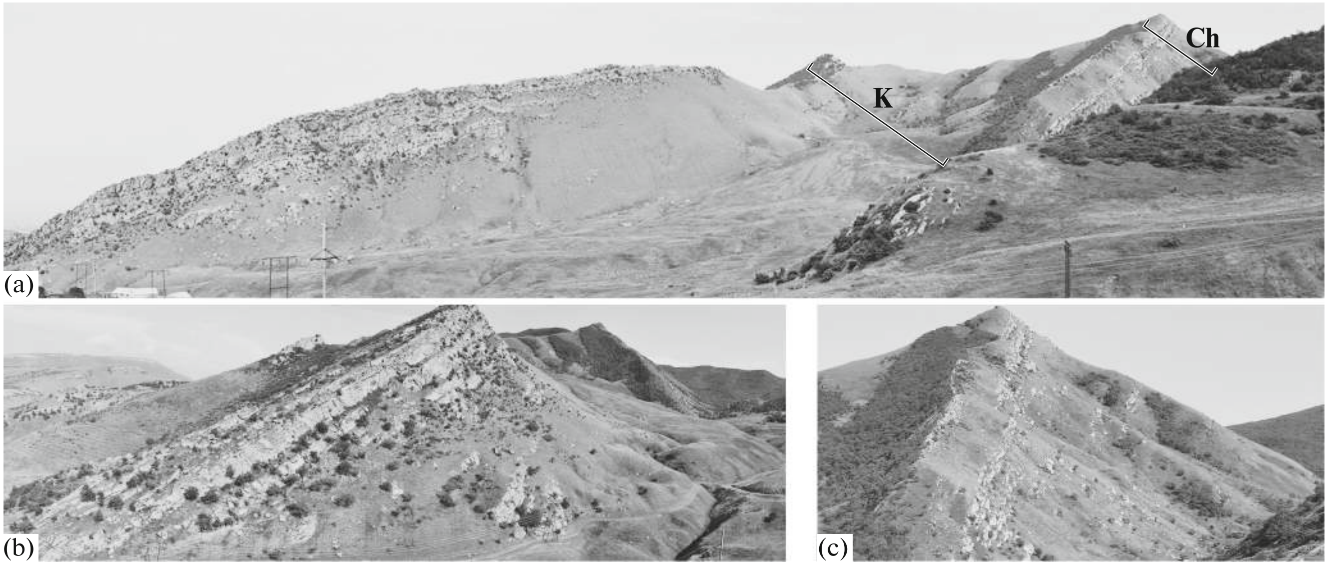

Fig. 2. Sedimentary cycles of the first order in the Middle Miocene sequence (Buinak Pass section). (a) Panorama of the Chokrakian–Karaganian section, (Ch) Chokrakian (incomplete), (K) Karaganian; (b) upper part of the Karaganian sequence; (c) upper part of the Chokrakian sequence.

The upper boundary of SEH is commonly sufficiently regular. Initially, the SEH surface was likely undulatory after the seismic event, but high hydrodynamic activity and shaking of the deformed and weakly lithified sedimentary masses in the course of aftershocks promoted its flattening.

The SEH base includes a destructurized sandstone bed in some places. Its response to the seismic event obviously depended on the degree of lithification of sediments.

In the case of weak cementation, liquefaction of the bed material was complete and the newly formed sandy pulp was redistributed, resulting in the local development of sandy bulges or the thinning of beds to the minimum values up to the point of their complete pinch-out (Figs. 3a–3c). Correspondingly, liquefaction of the sandy material was responsible for instability, dislocation, and destructurization of the overlying sediments. In the case of partial lithification, the sandy bed could partly retain the primary fabric. Seismic shocks could produce the subhorizontal detachment and fracturing of beds and the thrusting of one bed over another (Figs. 4a, 4b). However, a partial liquefaction and redistribution of material in the bed could take place even in this case, resulting in variation of its thickness (Fig. 4a).

In the lower part of the Chokrakian SEH, the clayey–silty matrix includes numerous flattened lenticular fragments of sandy interbeds (Figs. 3a, 3c, 3f). This rock type was related to the destruction of sediments initially representing a member of frequent intercalation of clayey and sandy beds. The SEH also includes relatively large (several meters long) rock fragments that occur locally at some angle to the bedding and impart the appearance of overthrusting (Fig. 3a). One can also see deformed fragments of sandy beds making up acute folds (Fig. 3b). If the sediments were initially composed of relatively similar (in grain size) clayey and clayey–silty sediments, impact of seismic shocks upon them was accompanied by their plastic deformations (Figs. 3a, 4c).

Evidence of liquefaction of the sandy material is also observed beneath the SEH – inside sequences that usually retained the primary bedded structure. Redistribution of the sandy pulp inside the beds provoked a marked change of their thickness. Here, one can also observe the formation of horizontal detachments, overlapping of beds, and their duplication in some places (Figs. 3, 4).

In some intercalations of clays and sandstones associated with the SEH, seismic shocks provoked horizontal detachments inside the clayey rock beds and variations in the primary sedimentary structure of beds. The consequent offset and trituration of rocks obliterated their sedimentary bedding and the appearance of new secondary deformations.

Clastic (neptunic) dikes[1] and sills are an integral part of seismic complexes. They represent diverse injections of sandy bodies differing in shape and bedding pattern (Fig. 5). Their association with destructurized sediments indicates that the horizons in question are related to earthquakes rather than passive gravitational solifluction. Analysis of neptunic dikes in

[1] Terms "injection," "neptunic," and "clastic" dikes are used here mainly as synonyms. Often it is rather difficult to determine the passive (downsection or upsection) mechanism of seismogenic fracture filling by the sandy material under pressure.

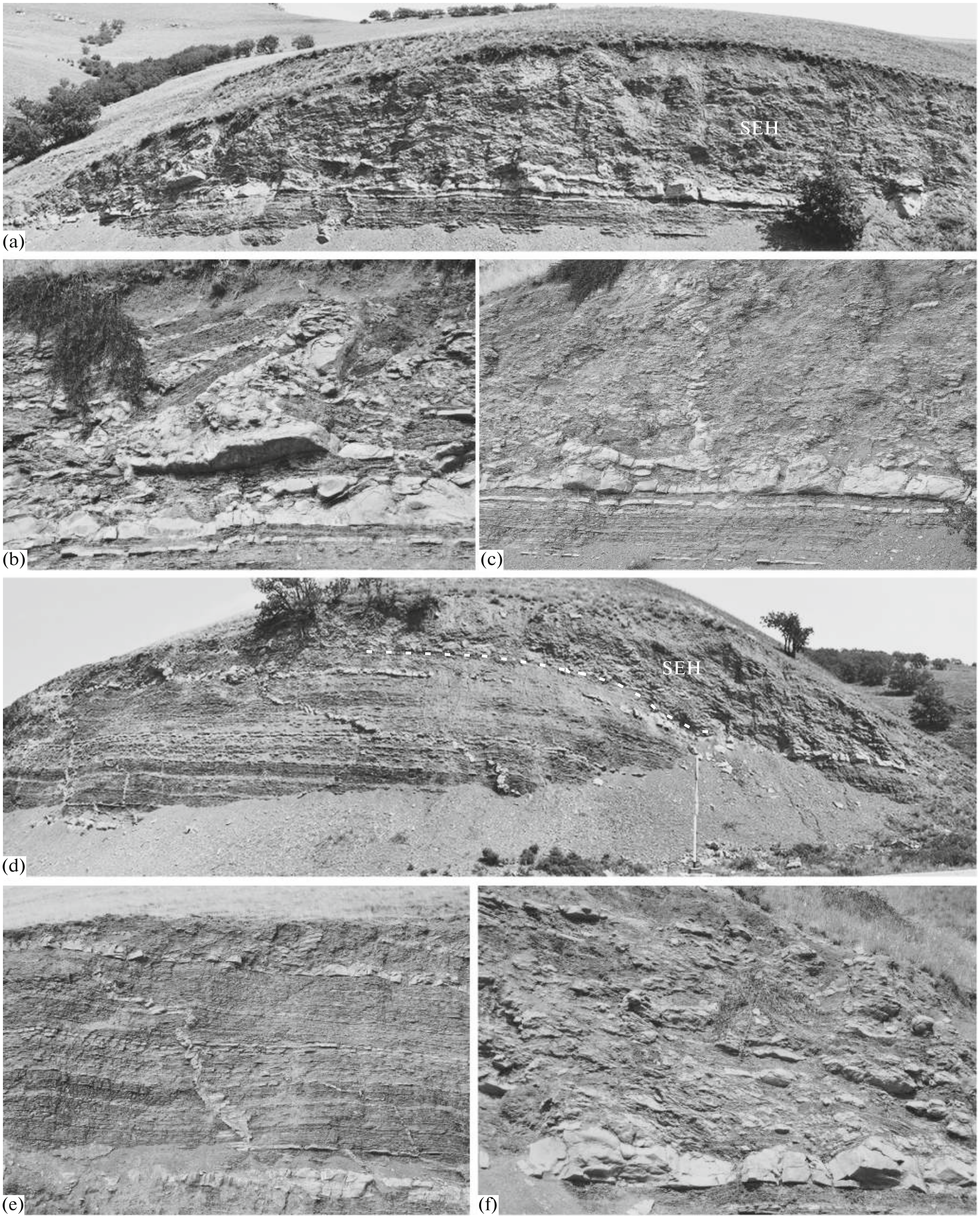

Fig. 3. Seismic complexes in the lower part of the Chokrakian section. (a) Deformed and destructurized sediments in the SEH and their contact with the underlying undeformed rocks intruded by neptunic dikes; (b, c) SEH fragments: (b) plastically deformed sandstone bed making up a lying fold, (c) clastic dike across the SEH; (d) SEH with irregular base underlain by undeformed sediments containing both subvertical and inclined neptunic dikes; (e) intricate neptunic dikes; (f) SEH fragment with a high degree of disintegration of the Middle Miocene sandy–clayey sediments (right part of outcrop in Fig. 3d).

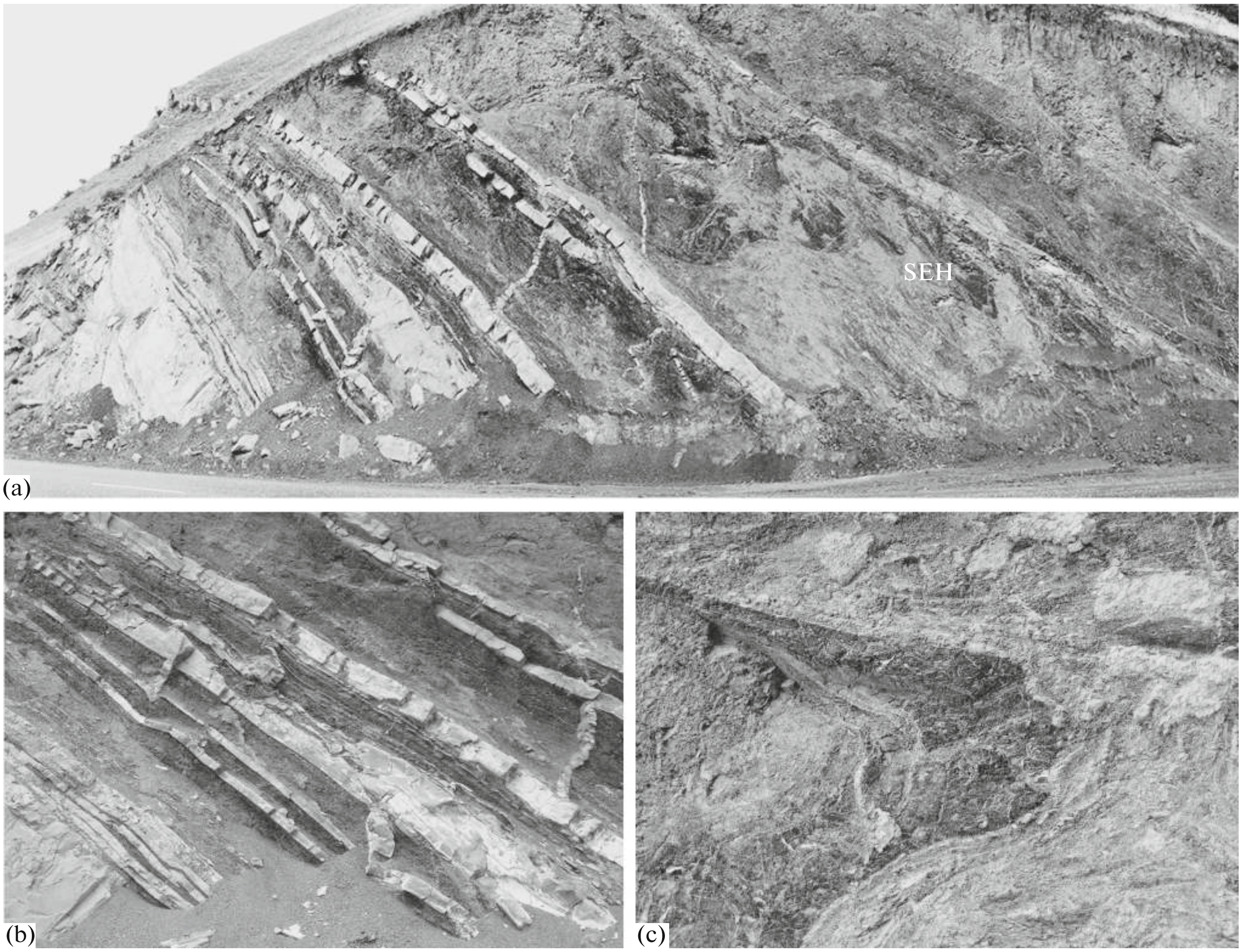

Fig. 4. Seismic complex in the middle part of the Chokrakian section. (a) SEH and the underlying sandstone and mudstone intercalation with traces of seismogenic deformations (low-angle overthrust faults, interbed detachments, liquefaction of the sandy material, and others); (b)) morphologically different injection bodies in the intercalation; (c) plastic deformations of clayey–silty sediments in the SEH.

the section revealed the dependence of their orientation on distance from the SEH.

The neptunic dikes deviate from the SEH and intrude the underlying undeformed sequence over different depths. However, neptunic dikes were formed mainly along subvertical fractures in the relatively deep (a few tens of meters below the SEH) and appreciably lithified sediments. In Fig. 5f, which shows dikes of this type, the base of the Chokrakian sequence includes sandstone beds a few decimeters thick. Owing to the seismic event, the beds underwent liquefaction and the sandy pulp was injected along fractures into the overlying sediments, resulting in the formation of dikes (length up to 10 m or more) that pinchout upward the section. In addition to open fractures, numerous closed fractures appeared in the clayey rocks (Fig. 5f), and the residual interstitial water percolated along these fractures due to the compaction of clayey sediments.

The seismogenic jointing pattern changed near the SEH. In addition to subvertical fractures, inclined fractures also appeared in the sediments underlying the SEH down to a depth of ~10 m. Consequently, the sandy pulp was injected into fractures of any orientation to make up dikes of different shapes. As seen in Figs. 3c and 3d, they deviate from the SEH at different angles (from 90° to 30°). A similar variation is observed in the spatial orientation of different parts of a single dike (Fig. 3e). One can see a frequent transition of the dike-shaped bodies into sandy sills. Although usually oriented almost horizontally, the sills can "jump" into another level of sediments (Figs. 5b, 5c). Sometimes, the morphology of injection bodies changes from dikes to sills with intricate mutual transitions (Fig. 5e).

Let us note that the SEH can also include relatively short (a few meters long) sandy dikes that are missing in the host clayey sediments (Fig. 3c). Their formation

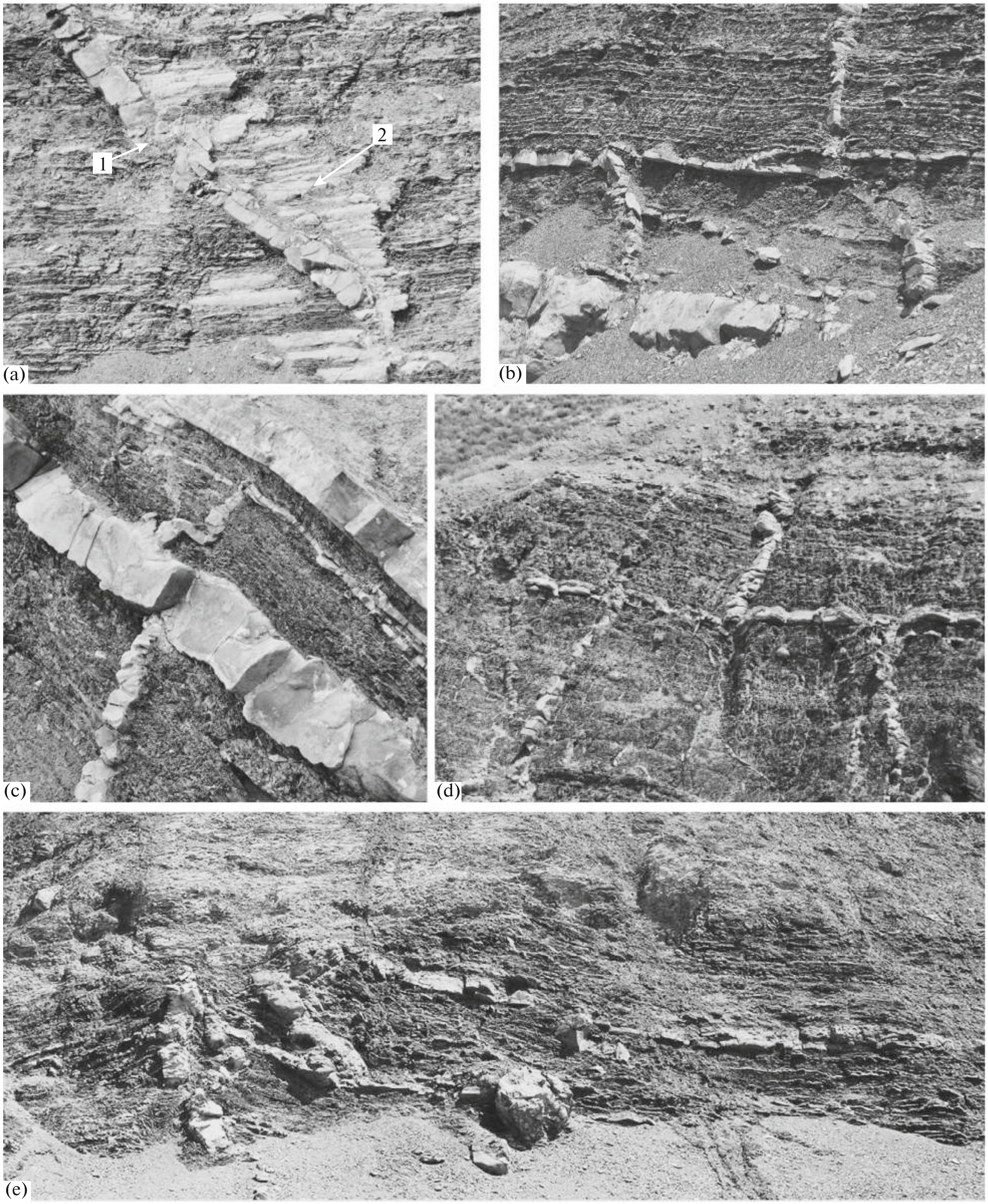

Fig. 5. Neptunic dikes of different shapes in the Chokrakian sediments. (a) Cruciform dikes oriented perpendicular (1) and parallel (2) to the outcrop plane; (b–e) interrelations of subvertical dikes with sills and sedimentary sandstone beds; (f) dikes at the base of Chokrakian- sequences (extending away from the underlying sandstone bed with explicit signs of the sandy material liquefaction); (g) dike with an echelon structure cutting the SEH; (h) upward and downward wedging dike – probable apophyse of a major large injection body; (i) dike fragmented due to seismogenic detachments of interbeds and dislocations of the dike-hosting beds along them; (j-1) dike related to the multiple injection of the sandy pulp into the fracture; (j-2) closeup of a fragment of dikej-1: one can see sulfide concretion at the center (inside the ellipse) and traces of solution percolation in the dike.

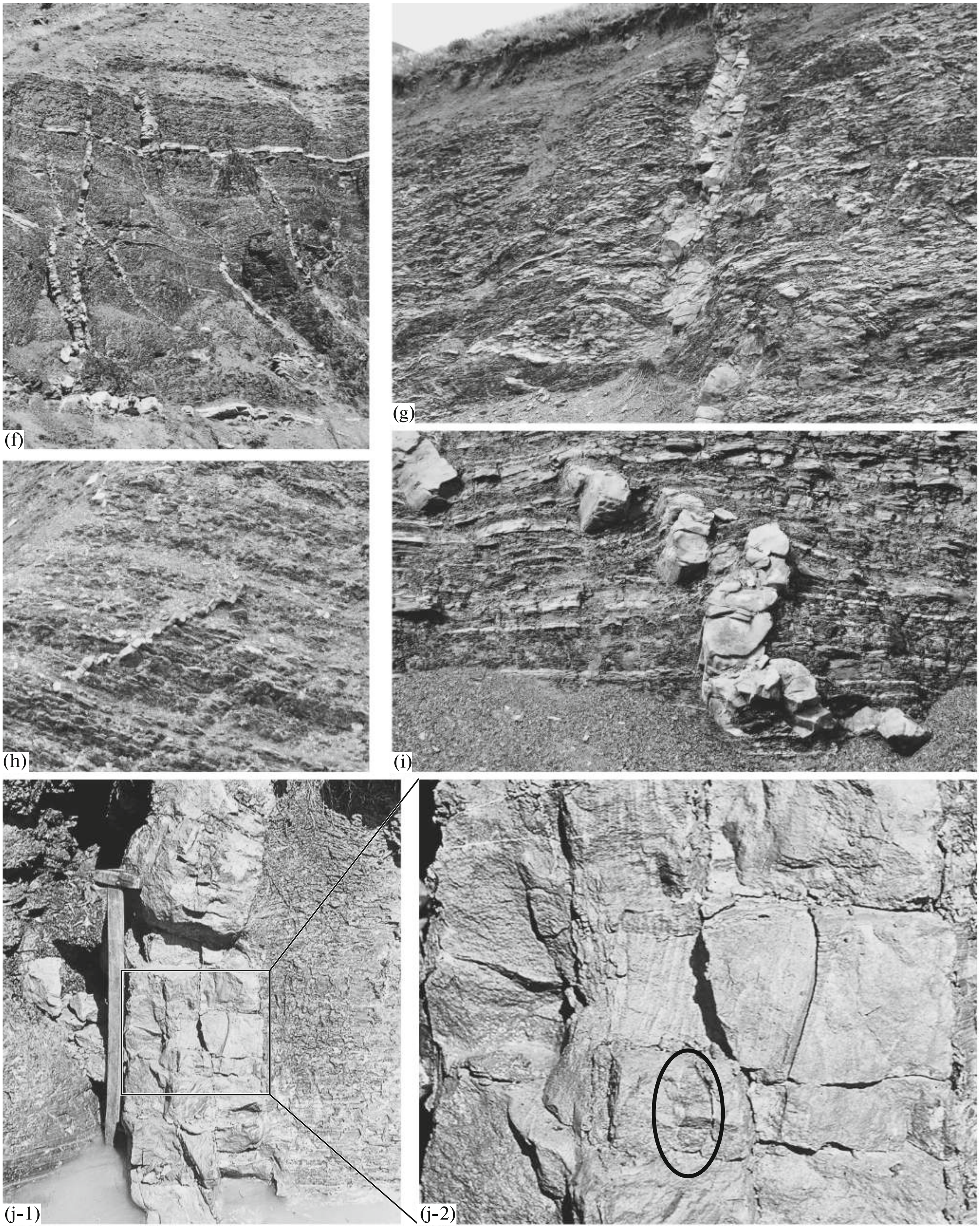

Fig. 5. (Contd.)

is attributed to aftershocks of the main seismic shocks. At the same time, relatively short dikes deviating from the SEH over a few meters into the overlying sediments (Fig. 4a) are likely related to the subsequent seismic events. In some places, one can also see upward and downward wedging dikes (Fig. 5h) that represent the apophyse of a larger injection body hidden in the sequence.

After the formation of dikes, the compaction of host clayey sediments was often accompanied by their fragmentation, "slippng" of fragments relative to each other, and development of a specific echelon-type structure of dikes (Fig. 5g).

If the zone of active influence of earthquakes included intercalations of sandy and clayey rocks, liquefaction of the sandy material gave rise to interbed dikes (Figs. 4a, 4b). They could unite different beds with the liquefied material into a single system and foster the overflow of the sandy pulp from one bed to another.

Given that the formation of dikes was triggered undoubtedly by subvertical or inclined fractures, the appearance of sills was likely related to some other reasons. As noted above, the impact of earthquakes upon the sedimentary sequence is manifested as interbed slipping of sediments, subhorizontal detachments, homogenization of rocks in the zone, and disappearance of the primary sedimentary bedding. These zones can differ in morphology and thickness, but their similarity is suggested by local distortions in the continuity and decompaction of rocks. Such zones in sediments were likely most favorable for injection of the liquefied sandy material under the influence of impulsive increase in the sandy pulp pressure due to seismic shocks. The interbed slipping could be fostered by the following situation: the Chokrakian sediments (particularly, their lower part) are enriched in organic matter, which served as a specific lubricant. The interbed dislocation of rocks likely provoked fragmentation of the dike at different levels and its downsection transition into a stratiform body (Fig. 5i).

Some dikes were formed by the multiple injection of sandy pulp into the fracture (Yaryk-su River section) (Kholodov and Gavrilov, 1977), resulting in the specific dike-in-dike structure (Figs. 5j-1, 5j-2). In some places, the dikes include sulfide concretions, probably, related to the migration of reduced interstitial waters into the dikes from the host organic-rich sediments (Fig. 5j-2).

Issue of the maximum depth, where the seismic event can affect liquefaction of the sandy material, is important for understanding regularities in the distribution of intrusion bodies in the sedimentary sections. This is determined to a great extent by the degree of lithification and cementation of the sandy material. In general, Middle Miocene sandstones are composed of the oligomictic, relatively weakly cemented quartz material, which could be subjected to liquefaction at some depth (probably, a few hundreds of meters). At the same time, active diagenetic processes took place in the adjacent organic-rich clayey sediments, and interstitial waters therein were saturated with Ca–Mg–Fe bicarbonates (Gavrilov, 1977, 1982). Upon compaction of the clayey sediments, bicarbonates together with the squeezed out waters could percolate in sandstones and give rise to carbonate cementation in some places. Such sandstones were already immune to the secondary liquefaction and pulp formation. According to (Kholodov, 1983, 2013), neptunic dikes could be formed at much greater depths.

High seismicity of the region in the Middle Miocene was also likely responsible for the formation of large slabs (fragments) of older sequences inside the lower Chokrakian sediments (Fig. 6). For example, the highest point in the Buinak Pass shows the contact of clayey sediments characterized by notably different contents of the sandy–silty material. Here, the lower part the outcrop includes mudstones with thin interbeds of silty sandstones that are typical of the lower Chokrakian. They are overlain by much purer clayey rocks (without or with rare sandy–silty interbeds). This sequence contains beds of lenticular Mn-siderite concretions that are similar to those in the Zuramakent Formation (the uppermost unit in the Maikop Group).

The contact of these rocks includes a horizon (~2 m thick) of boudinaged, destructurized, and locally folded rocks with a yellowish jarosite-type coating. Fragments of sandy beds therein are inclined along one side to make up a scaly structure – system of small overthrust faults (Fig. 6). The base of this horizon truncates the underlying sediments at a low angle. Several lithological properties of the "jarosite" horizon make it possible to determine the fault plane, along which the slab (large olistolith) of sediments from the uppermost part of the Maikop Group was thrusted over the lower Chokrakian sediments. The upper contact of slabs is closed and its thickness is arbitrarily estimated at 13–15 m. Most probably, this slab slipped over the Talgin paleouplift that rose during the Cenozoic. The northwestward displacement of slabs is indicated by the scaly structure of the fault horizon. In this case, however, the formation of olistolith was provoked by earthquake, as suggested by signs of liquefaction of the sandy material in the Chokrakian sediments beneath the fault plane. During the seismic event and dislocation of slabs, rocks in the upper part of the Maikopian were already lithified significantly, and the slab represented a sufficiently rigid body. At the same time, its displacement over several meters was obviously reflected in the internal structure – one can see minor distortions in the primary bedding of rocks and small detachments. We previously noted analogical slab of the Zuramakent sediments in the Chokrakian section along the Sulak River. It is important that the lower part of the Maikopian sequence includes large Upper Cretaceous–Lower Paleogene olistoliths and olistoplaques slipping down from the Talgin paleouplift.

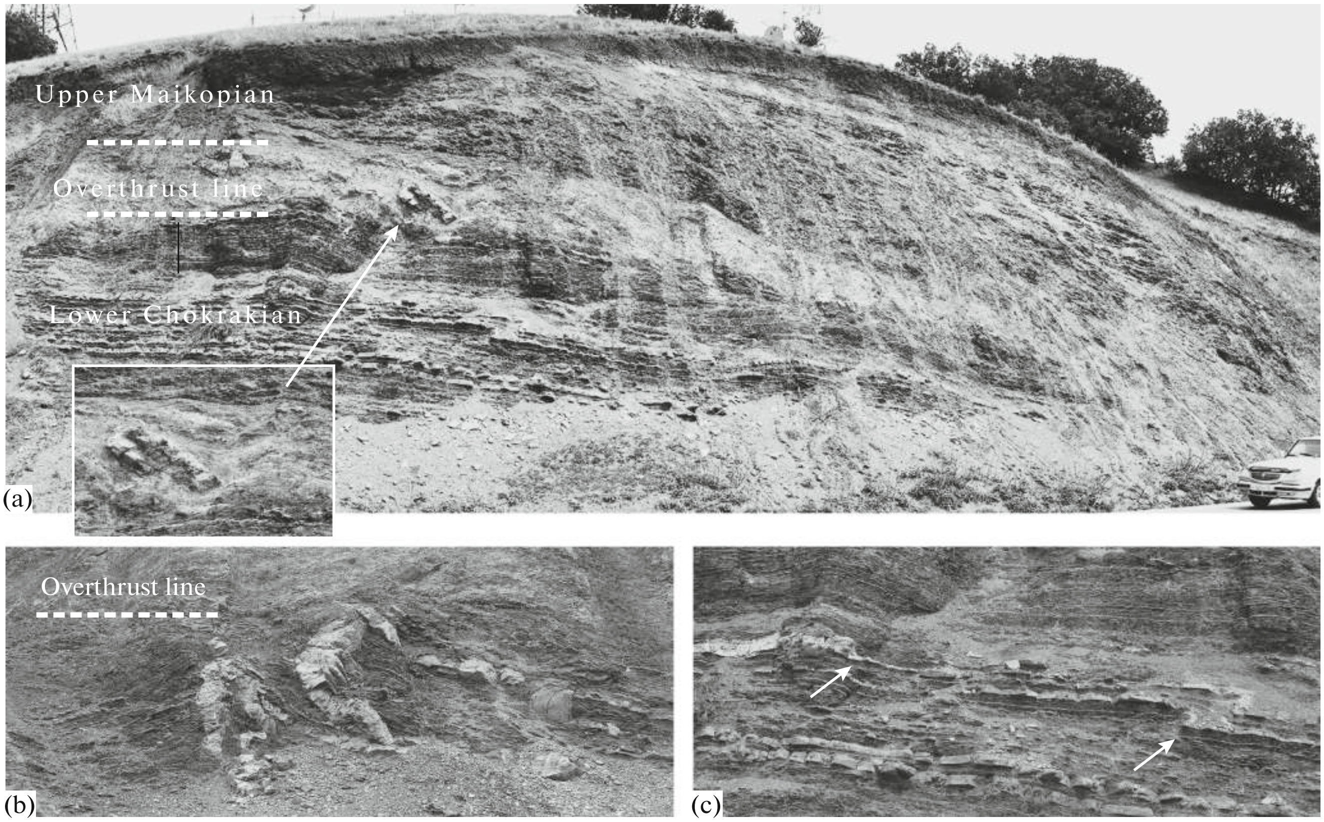

Fig. 6. Slab of upper Maikopian sediments in the lower Chokrakian sequence.
(a) Interval between the lower Chokrakian and upper Maikopian (Zuramakent Horizon) rocks is filled with destructurized rocks (pale-colored), along which Maikopian slabs were dislocated (inset shows a fragment of the imbricate overthrust fault); (b) dike-shaped injection bodies beneath the overthrust fault; (c) drastic variation of the bed thickness owing to liquefaction and redistribution of the sandy material (left) and plastic deformation of beds (right).

The relative analysis of seismic dislocations from different parts of the Middle Miocene sequence revealed their irregularity: the seismites acquire new patterns upward the sections because of variations in the lithology: the middle part of the Chokrakian sequence shows distinct sedimentation cycles of the second order (10–15 m); the lower part is dominated by clayey sediments; the middle part usually includes an intercalation of clayey rocks and sandstone beds; and the upper part includes the thickest sandstone beds.

Traces of seismic shocks are most prominent in intercalations of black clay and sandstone beds. As is evident from Fig. 7, disintegration of the primary sedimentary structure of sediments can be very intense. Moreover, the behavior of clayey and sandy rocks can be different. Owing to the seismic shock, the partly lithified clayey rocks were disintegrated into relatively acute-angle fragments, while the sandy rocks were subjected to liquefaction, resulting in numerous injections of pulp that filled up all possible fractures in the clayey rocks (Figs 7d, 7e). The crushing and disintegration of rocks was likely promoted by the mutual displacements of sandy beds. Such displacements also affected the sandwitched sandy–clayey horizons and promoted the development of the specific “seismic neptunic-net” structure. Sometimes, the mutual displacements of beds produced the torsional structure of beds (specific “rolls”). Liquefaction of the sandy material in sandstone beds complicated the morphology of such structures (Fig. 7b).

Thick sandy beds are marked by a typical irregular base related to their displacement over the clayey rocks (Figs. 7a, 7c). In some places, seismic shocks provoked the disruption and boudinage of beds. In this case, the sedimentary structure of clayey sequences was almost completely changed into a disordered chaotic pattern with traces of small internal overthrust faults (Figs. 7a, 7c, 8a, 8b).

The seismic shocks also produced subsidence structures, where a part of the sandstone bed laterally confined by fractures subsided into the underlying clays (Fig. 8d). Together with the sandy bed, some part of the overlying clayey sediments also subsided, resulting in the formation of a block of unconsolidated clayey rocks above the subsided block and intrusion of the sandy pulp. We assume this mechanism for the formation of a thin (a few decimeters) sandy bed, which

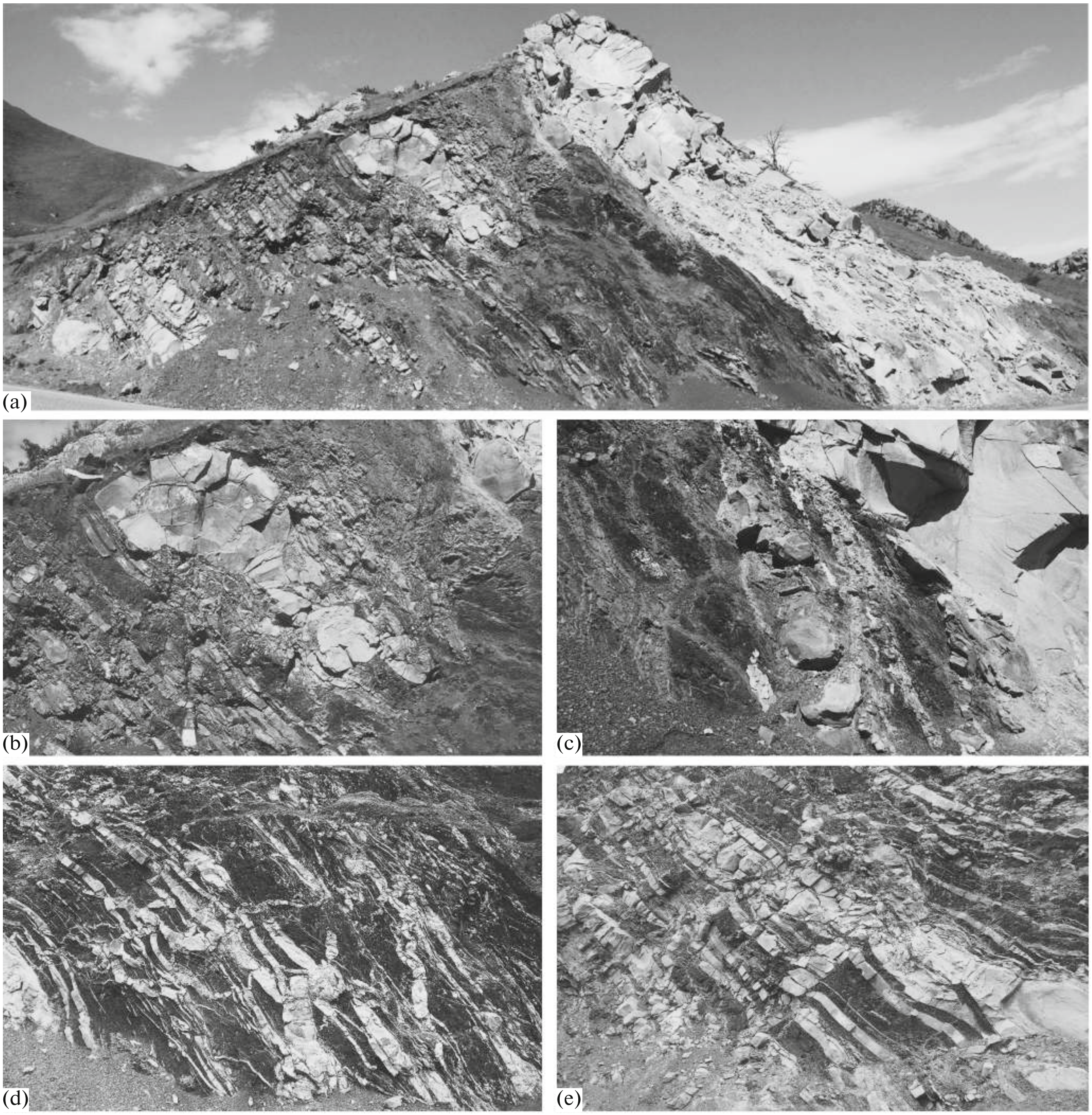

Fig. 7. Seismogenic distortions in the structure of upper Chokrakian sedimentary cycles of the second order. (a) General view of sedimentary cycles; (b) disrupted sandstone bed with signs of liquefaction and "warping" of the sandy material; (c) destructurized and fracture-intersected clayey rocks with fragments of disrupted sandy beds; (d, e) numerous fractures filled with the sandy pulp in the sandy–clayey intercalation.

overlies the subsided sandy bed and actually represents a sill (Figs. 8a, 8d).

Analysis of the distribution of seismites in the Chokrakian and Karaganian sedimentary sequences shows the following trend: in both cases, frequency and, probably, intensity of seismic events increased upward the section. In the lower parts of the studied sections, one can identify both intervals of seismic events and periods of the relatively seismic pause. The upper parts show diverse seismogenic structures, testifying to appreciably more frequent earthquakes. Here, it is much more difficult to identify a specific seismic complex, because frequent seismic complexes overlap each other.

Thus, during the formation of sedimentary cycles of the first order (Fig. 2), seismic activity increased gradually and reached the maximum at the final stage

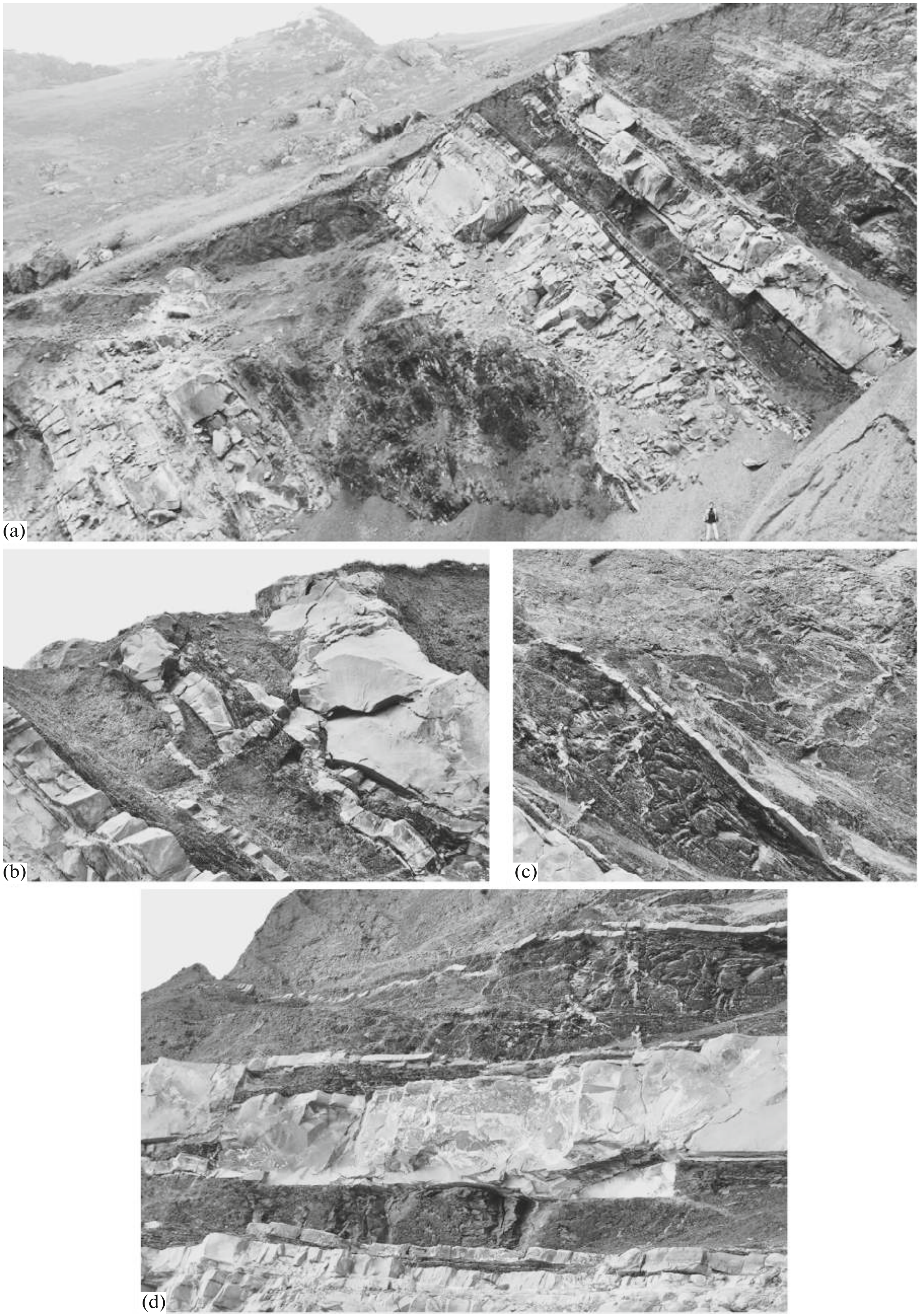

Fig. 8. Seismogenic deformations in the upper Karaganian clayey–sandy rocks. (a) General view of a fragment of the Karaganian sequence subjected to the seismic impact; (b) seismically deformed sandy bed and intricate injection bodies; (c) destructurized clayey–silty sediments with traces of overthrusting and numerous fracturing; (d) fragmentation of a sandy bed and its partial slumping into the underlying clayey sediments.

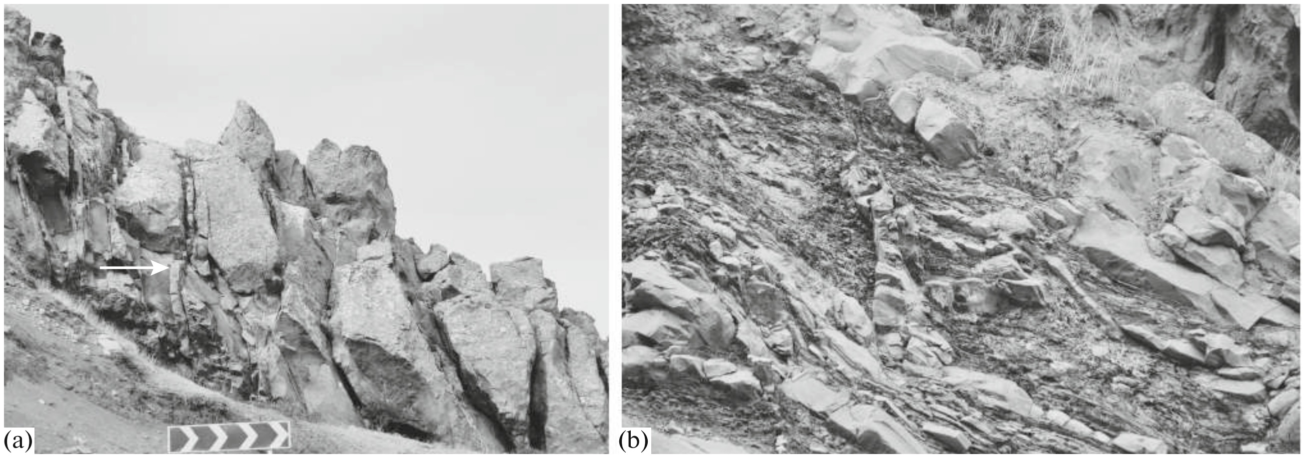

Fig. 9. Seismogenic structures at the top of Chokrakian sedimentary cycles of the first order. (a) Seismogenic fractures in sandstones at the Chokrakian roof (arrow shows a neptunic dike in one fracture); (b) injections into the destructurized sediments underlying sandstones at the Chokrakian roof.

that preceded the onset of a new vigorous impulse of subsidence of the Middle Miocene basin floor. The regularly oriented rough jointing in sandstones on the top of the Chokrakian sedimentary cycles of the first order is also likely related to the impact of strong earthquakes (Fig. 9a). This conclusion is supported by the following fact: the sandy bed is underlain by intercalations of the sandy and clayey beds with numerous traces of liquefaction of the sedimentary material and formation of diverse injection bodies (Fig. 9b). At the same time, the dikes were also formed along fractures crosscutting the sandy horizon (Fig. 9a).

The formation of diverse and numerous seismites in the Middle Miocene sections in Dagestan and adjacent regions was caused to a great extent by the large-scale liquefaction of the sandy material, which governed the structure and specific fabric of seismic complexes (Dagestan-type seismites).

Analysis of the distribution of traces of earthquakes in the Middle Miocene sections over a large area extending from Dagestan to North Ossetia shows that their number and inferred intensity decrease toward the west. In addition to Dagestan, a sufficiently great number of the Dagestan-type seismites is recorded in eastern Chechnya (Yaryk-su River basin). However, the number is considerably smaller and only single clastic dikes are observed in the central areas (e.g., Chanty-Argun River basin, Elistanzhi River section). At the same time, sections in Chechnya and Ingushetia show seismic patterns differing from the Dagestan-type seismites. Although such bodies can be classified as seismites, they are related to a weaker seismic impact upon rocks.

Mineralogical-geochemical evidence of earthquakes. The Middle Miocene sections in Chechnya and Ingushetia enclose subvertical carbonate bodies related to seismic events (Gavrilov, 1978, 1982). In terms of morphology, they represent pyramidal carbonate concretions and underlying small "carbonate dikes."

Pyramidal concretions and carbonate dikes are usually confined to certain intervals of sections, which include an alternation of brown clays (enriched in organic matter), gray clays (with a minor content of C_{org}), siltstones, and sandstones. A typical horizon of such type occurs in the upper Chokrakian section exposed along the Elistanzhi River in Chechnya (Fig. 10). The structure of this section is as follows.

Bed 1. Weakly cemented quartz sandstones. Thickness 3.5 m.

Bed 2. Dark brown organic-rich clays (C_{org} 3.5–4%). Thickness 1.8 m. Contact of Beds 1 and 2 is sharp. The contact zone includes large siderite lenses (up to 2–2.5 m across and 0.1–0.2 m thick). Bed 2 includes five interbeds of mainly siderite concretions (Figs. 10f, 10g).

Bed 3. Light gray, obscure-bedded silty clays. Thickness ~1.5 m. The bed contains numerous pyramidal concretions and carbonate dikes (Figs. 10b–10e).

Bed 4. Greenish gray, fine-grained, nonbedded sandstone. Thickness 0.8–0.9 m. Contains large dolomite lenses (length 5–8 m, thickness 0.7 m).

Bed 4 is overlain by a fragmentary outcrop of clayey sediments, but this interval is commonly closed.

The clayey rocks (Beds 2 and 3) are characterized by the presence of subvertical fractures that are usually curved. In Bed 3, some fractures are filled with the sandy–silty material from the overlying sandy bed; i.e., they make up small clastic dikes (width 3 to 4 cm). However, the fractures are usually observed as millimeter-scale closed structures; i.e., they are not filled with sand. Fractures at the base of Bed 2 lean against the siderite concretions lying at the contact with the underlying sandstones (Fig. 10f).

The surface of early diagenetic ellipsoidal concretions is commonly even. However, the surface of some sectors in Bed 2, where the fractures lean against the concretions, shows elongated carbonate knolls. Along some fractures in this bed, one can see specific carbonate "bridges" that connect concretions from different beds (Figs 10f, 10g).

Pyramidal concretions in Bed 3 are composed of several discoid (pancake-shaped) nodules overlying each other (diameter 5–30 cm, height 0.2–0.7 m) (Figs. 10d, 10e, 10h). The subvertical concretions are surrounded from the top and bottom by clay layers, suggesting their formation before the final compaction of host rocks.

Another variety of the subvertical formation is represented by dike-shaped bodies (height 1–1.5 m, width 10–15 cm) and their central zone is crosscut by fractures filled with the sandy–silty material from Bed 4. These small neptunic dikes and adjacent clays (a few centimeters thick) connect the siderite concretions tightly and make up a single subvertical carbonate dike.

The gray silty clays (Bed 3), which accommodate the pyramidal concretions and carbonate dikes, occupy an intermediate position between the brown clays (Bed 2) and sandy rocks (Bed 4). The gray clays are marked by very low contents of C_{org}. Consequently, they lack iron bicarbonates that could make up the subvertical siderite bodies.

In contrast, diagenetic concretions were formed in the brown clays (Bed 2) at that time, and interstitial waters therein were saturated mainly by iron bicarbonates. It should be emphasized that the pressure of interstitial waters here was appreciably higher than in the adjacent Beds 1, 3, and 4, resulting in the primary high inundation of the carbonaceous sediments and a much stronger diagenetic compaction of sediments, relative to the adjacent beds (Gavrilov, 1978, 1982).

Study of intercalations of clayey and sandstone beds revealed that the pressure of interstitial waters during the compaction of clayey sediments is higher than in the sandy varieties. At the same time, outflux of water can take place along both upward and downward from the consolidating clayey sediment, but the boundary between zones with different directions of solution migration passes somewhere at the middle of the sediment bed (Mukhin, 1965; Magara, 1974; and others). In this process, the water is squeezed out over the whole clay/sandstone contact area. However, if additional permeable zones are developed, they serve as the main pathways for the migration of solutions.

In the Middle Miocene sediments, seismic shocks in the clayey sediments produced fractures, which began to serve as additional pathways for the outflux of the interstitial waters. The squeezing of solutions and their migration along fractures from the high-pressure beds to the relatively low-pressure ones was an important favorable condition for the formation of subvertical concretions.

Their formation was also promoted by significant discrepancies in the geochemical composition of interstitial waters in Beds 1–4. Owing to different contents of C_{org}, the water buried in each bed was also characterized by a specific composition in the course of early diagenesis. During the formation of a permeable pathway to Bed 2, the carbon dioxide pressure was high because of the continuing destruction of organic matter. In addition, siderite concretions were formed here, and the interstitial solutions were saturated with iron bicarbonates with a minor admixture of Ca–Mg bicarbonates.

The seismic event provoked the appearance of fractures in these rocks and initiated the migration of iron bicarbonates from brown clays in the adjacent beds (Beds 1, 3, 4). Input of solutions from the high-pressure zone (Bed 2) into the gray clays promoted the degasification of fluids, resulting in the precipitation of the least soluble iron carbonate and, partly, magnesium carbonate. Solutions percolated along the most permeable zones (tubular channels) in the closed fractures, resulting in the formation of pyramidal concretions composed of Mg-siderite. In the sand-filled fractures, solutions could percolate over the entire permeable zone to make up the dike-shaped bodies. Calcium and magnesium bicarbonates left in the solution could reach the sandstone (Bed 4) and participate in the formation of dolomite lenses here.

Since fluids migrate in the bedded clayey sediments to both top and bottom of the bed, the downward migration of a part of the interstitial solutions along the fractures promoted the formation of siderite lenses at the contact of Beds 1 and 2 (Figs. 10a, 10f). In clays of Bed 3, the solutions gradually lost $FeCO_3$, resulting in the appearance of elongated vertical concretions. At the above-mentioned contact with the highly permeable sand, however, the degasification was rapid and iron carbonate was precipitated at the interface of two contrast (in lithology and geochemistry) beds.

Sometimes, as a result of the seismic impact upon the nonlithified sediments and their consequent "shaking," the newly formed gaseous products of early diagenesis (including CO_2) were transferred from the sediments to the suprabottom water. The migration of gas bubbles in the sediment promoted the formation of fine subvertical channels enveloped with carbonates of different compositions due to the distortion of equilibrium conditions, resulting in the formation of subvertical carbonate concretions (Fig. 10h). In other places, the seismic shaking of organic-rich sediments distorted the primary bedded structure of sediments, and the migration of bicarbonates was rather chaotic. These processes fostered the formation of unusual intricate concretions rather than the traditional ellipsoidal concretions (Fig.10i) (Gavrilov, 1982).

The subvertical pyramidal concretions and carbonate dikes are irregularly distributed in the Middle Mio-

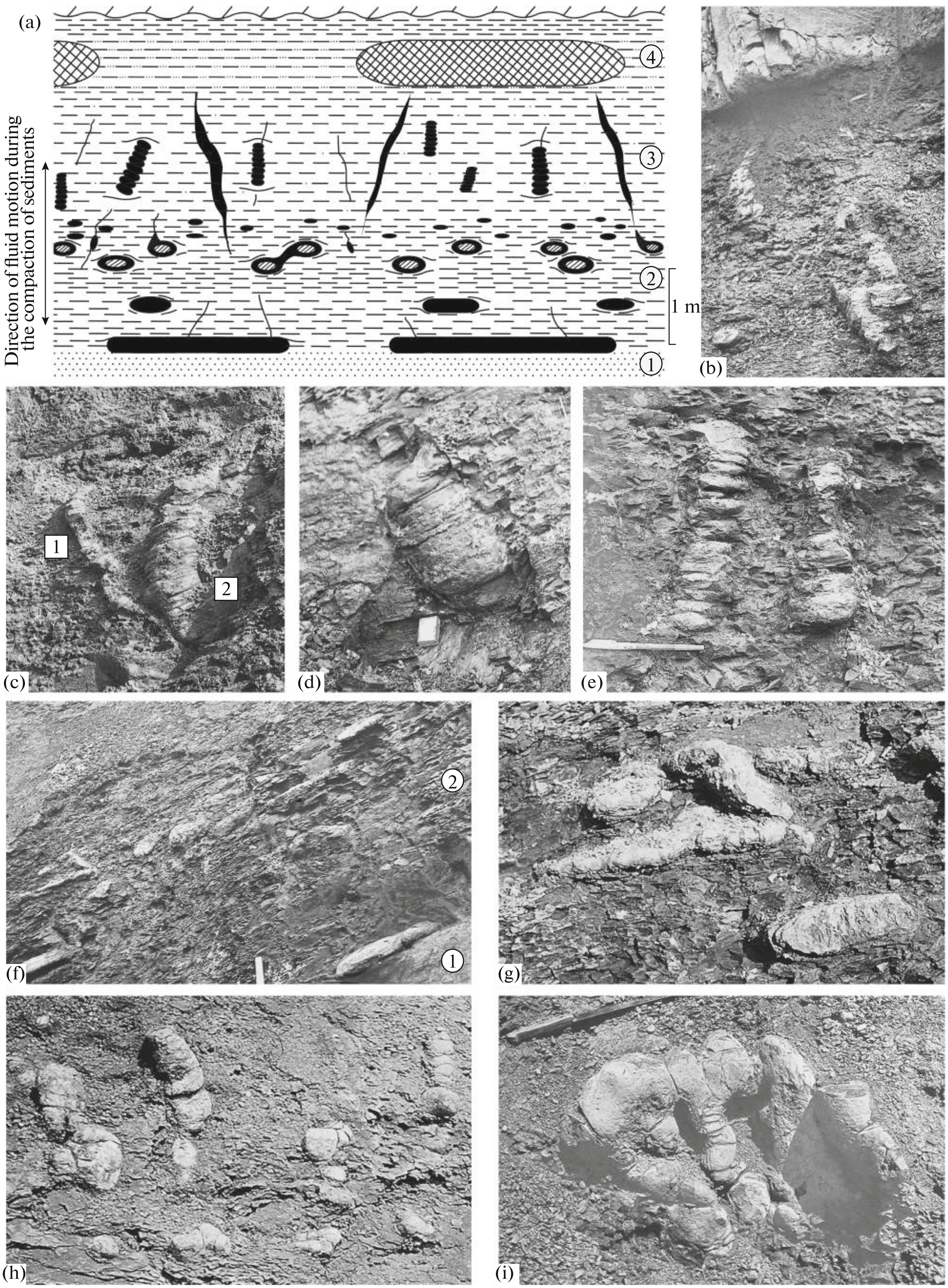
(a)
4
3
2
1
1 m
Direction of fluid motion during the compaction of sediments
(b)
(c)
1
2
(d)
(e)
(f)
2
1
(g)
(h)
(i)

Fig. 10. Subvertical carbonate concretions and dikes formed by the migration of diagenetic solutions along the seismogenic fractures, according to (Gavrilov, 1977, 1982). (a) Scheme of the outcrop with subvertical concretions and dikes (numerals designate intervals with lithologically different sediments along the Elistanzhi River section): (1) quartz sandstones, (2) organic-rich clays with concretion interbeds, (3) gray silty clays enclosing subvertical siderite concretions and dikes, (4) fine-grained clayey sandstones with large dolomite lenses; (b) subvertical carbonate bodies in Bed 3 (the upper area of the image shows the lower portion of the dolomite lens; (c) carbonate dike (1) and pyramidal concretion (2) in Bed 3; (d, e) pyramidal siderite concretions: (e) Fortanga River section; (f) contact of sandstones (Bed 1) and brown clays (Bed 2) (the contact zone includes large siderite lenses); (g) siderite bridges that appear along the seismogenic fractures and connect concretions in different beds; (h) subvertical pyramidal concretions; (i) subvertical intricate siderite bodies (Fortanga River section).

cene sequence in the eastern Caucasus. In the zone of maximum seismic activity (Buinak Pass section, outskirts of Makhachkala), we did not detect such formations. Four levels of subvertical concretions were recorded in the upper part of the Middle Miocene sequence (Karaganian sediments) in the Yaryk-su River section (river between Dagestan and Chechnya). Main traces of high seismicity are confined here to the upper half of the Chokrakian sequence, and seismicity was distinctly attenuated in the Karaganian time. Further in the westward Middle Miocene sections exposed along the Elistanzhi (Chechnya) and Fortanga (Ingushetia) rivers, pyramidal concretions occur in the upper half of the Chokrakian sequence (Gavrilov, 1982). In the coeval sections in North Ossetia, we did not record explicit traces of seismic events, probably, due to variations in the lithology of sediments and, first of all, decrease in the depletion of rocks in C_{org}. Thus, we can conclude that the small carbonate dikes and pyramidal subvertical concretions were formed in sediments subjected to the impact of moderate seismic events. These shocks did not lead to considerable distortion of the primary sedimentary structure of sediments, but produced only subvertical jointing in the partly lithified sediments. Interstitial solutions migrated along fractures from the consolidating sediments and the diagenetic carbonates were precipitated along them.

Our observations suggest the following assumption. Despite the general high seismic activity in the eastern Caucasus in the Middle Miocene, maximum intensity of seismic events was characteristic of the late Chokrakian area, as well as adjacent parts of the paleobasin in Dagestan.

SEISMITES IN THE CLAYEY SEQUENCES OF THE MAIKOP GROUP[2]

It is much more difficult to find evidence of paleoearthquakes in the relatively monotonous clayey sequences than in the Middle Miocene sandy–clayey sections. Nevertheless, some typical signs recorded in the sediments make it possible to determine the influence of seismic events therein.

[2] In this work, the Maikop Group is understood as the Oligocene–lower Miocene sequence, which is subdivided into several formations, according to (Shatsky, 1929), including those mentioned in the text: Khadum and Zuramakent (lower and upper part of the Maikopian, respectively).

The formation of sediment intervals with the clayey rocks crosscut by numerous fractures is among the consequences of paleoearthquakes. If the near-surface beds of the Maikopian basin underwent the seismic impact, the sediments acquired a specific cellular pattern owing to the development of jointing. Against the background of dark gray mudstones, such fractures are clearly distinguished by the ocherous red color related to the oxidation of pyrite dissemination in the rock.

Some horizons of the cellular mudstones are overlain by sandy interbeds with furrows suggesting the flow-related (turbidite) genesis of the sandstones (Figs. 11a–11c). Their co-occurrence is not accidental: the jointing was related to the seismic shock, which was also responsible for the detachment of sedimentary masses from the slopes of ancient seamounts and the formation of mudflows above the fractured horizons (Chirkei section, Dagestan).

In the deeper beds of the sequence, which were more lithified during the seismic impact, the jointing was chaotic in some places (Fig. 11d). In other places, it was developed as subvertical fractures with width ranging from a few millimeters to 1 cm or more (Fig. 11e). Such fractures are often filled with gypsum, which could be formed at later stages of lithogenesis or hypergenesis.

The lower Maikopian clayey sequence is marked by intraformational unconformities (~10°–15°). In sediments underlying the horizon with angular unconformity, one can see distortion of the primary horizontal bedding and abundant jointing. Rocks along fractures have an ocherous color owing to iron hydroxides. The interval above the unconformity plane is composed of dark gray mudstones without traces of distortion of the sedimentary structure and signs of jointing. The development of such interrelations between rocks with different properties is related to the seismic event, which provoked some alterations in the primary pattern of beds, their moderate deformation, and jointing. The subsequent period was marked by the accumulation of sediments without signs of the impact of seismic shocks.

A sufficiently high seismic activity in the region during the formation of the Maikopian sequences (primarily, its lower part defined as Khadum horizon) provoked the destruction of rocks and formation of horizons with a high degree of jointing. These processes developed the reservoir properties of clayey rocks. The Maikopian sequence in the northeastern Caucasus is mainly characterized by clayey sediments and low reservoir properties. The development of seis-

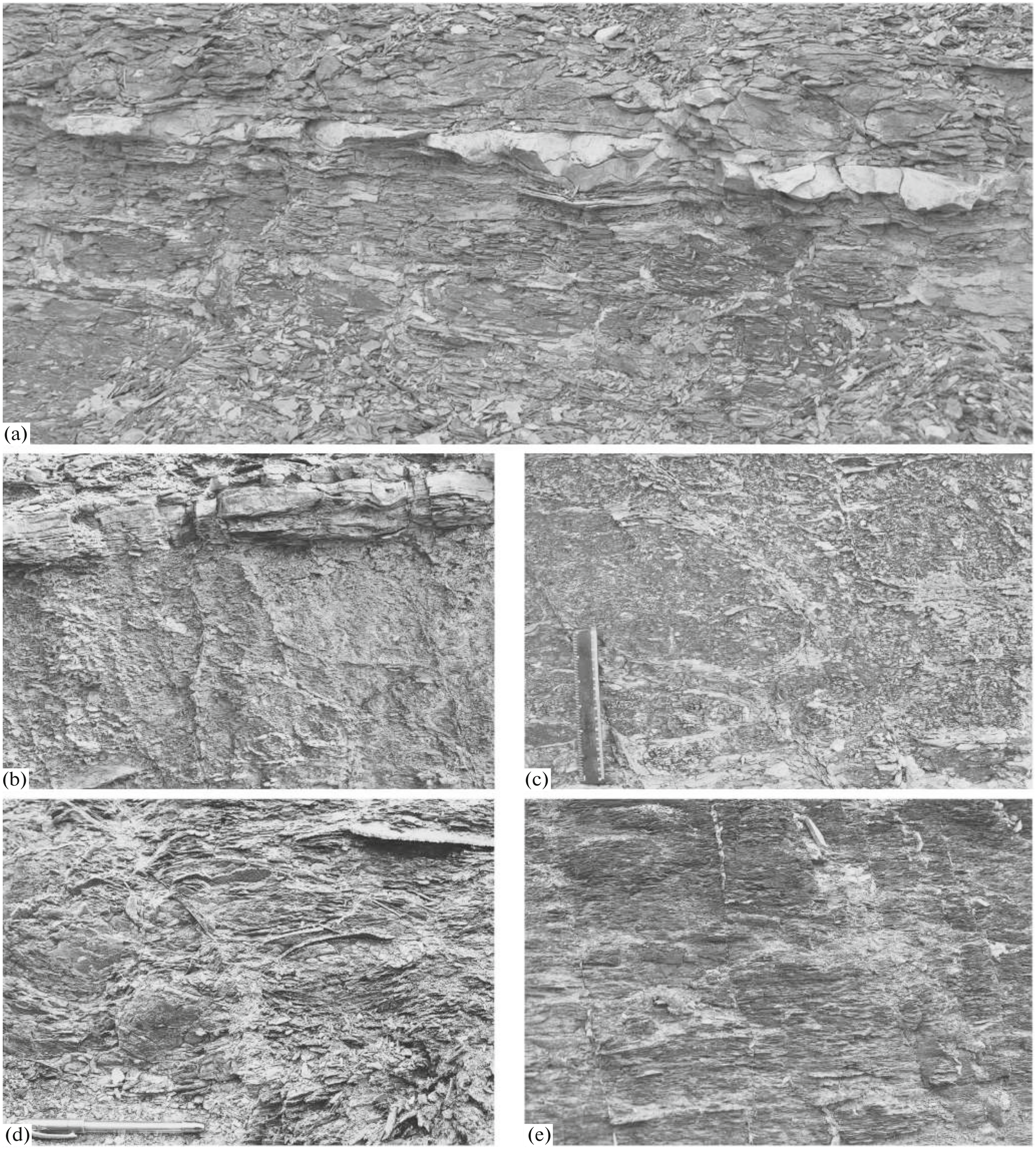

Fig. 11. Fracture-type seismites in the lower Maikopian clayey sediments. (a–c) Sandy bed with stream hieroglyphs on the base, which overlies an interval of clayey sediments with cellular fractures; (d) clayey rocks crosscut by differently oriented and gypsum-filled fractures; (e) clayey rocks crosscut by subvertical fractures.

mogenic jointing in them is very important, because the jointing created favorable conditions for the generation and accumulation of a significant amount of liquid hydrocarbons, which were exploited over a long period.

It is known that fissure-type reservoirs are also typical of the Bazhenovo Formation in West Siberia. Since the lithological evidence of earthquakes in the Mesozoic in the studied region is available (Mikulenko and Afanas'ev, 1969), we can also assume the seismogenic nature of jointing in this region.

SEISMITES IN THE LOWER AND MIDDLE JURASSIC ROCKS OF THE NORTHERN CAUCASUS

The thick (kilometer-scale) Lower–Middle Jurassic sequences of the northern Caucasus show numerous distortions of their primary sedimentary structure, and many of them are related to the impact of paleoearthquakes on the sediments.

Explicit seismite horizons are confined to the boundary of formations with different types of sedimentation. For example, the Lower Jurassic sequence in North Ossetia shows an abrupt transition from the sandstone-dominated sediments of the upper Pliensbachian Mizur Formation to the Toarcian clayey rocks. In the lowermost horizons of the Galiat Formation, one can see distinct traces of distortions in the sedimentary structure of sediments caused by their submarine slumping, which is emphasized by variation in the primary bedding of diagenetic concretions. These horizons also host neptunic dikes. Such association of slump deformations and dikes testifies to high seismic activity in this region in the initial Toarcian. Increase of seismicity was provoked by changes in the tectonic setting of the region – drastic spasmodic intensification of subsidence rate of the basin floor, which affected the sedimentation pattern and transition from the shelf-confined sandy sediments to the deeper and thicker clayey sequences.

The Aalenian clayey sediments of Dagestan (Igatli Formation) includes seismite horizons (1 to 2 m thick) that are similar to those described above in the Maikopian sequence.

The paleodelta in the Toarcian–Aalenian sediments of the eastern Caucasus shows signs of the displacement of large (kilometer-scale) sandy slabs downward the paleobasin slope (Gavrilov, 2005). Dislocation of the slabs was likely triggered by earthquakes, which became more frequent at the final stage of large sedimentary cycles, as in the Middle Miocene.

In Ingushetia, the relatively monotonous Toarcian sandy–clayey section hosts the Pui sandstones first reported in (Rengarten, 1931) from the Pui Settlement area. This horizon extends along the strike over more than 15 km. Its structure can be studied in at least two sites: Assa River valley and right bank of the Armkha River, a right tributary of the Terek River. The horizon is represented along the Assa River by an intercalation of sandstones and clayey siltstones. Thickness of the sequence is 120 m.

Study of the sequence revealed an appreciable distortion of its primary sedimentary structure: the sandstone beds are often truncated and the clayey–silty sequences abruptly pinchout in some places. This area also includes a bed composed of the dislocated sedimentary material. The bed is conformable with the bedding of rocks in some places and gently intersects sandstone beds in other places. It is exposed over many tens of meters. Less thick but similar (in structure) beds also occur at other levels of this sequence. The structure and bedding pattern suggest that these beds represent horizons of the detachment and dislocation of both whole sequence and its different parts relative to each other (Gavrilov, 1992).

Detachment horizons are also observed in another section exposed 12 km away from the first outcrop on the right bank of the Armkha River. Thickness of the Pui sandstones decreases here to 45–50 m. The lower detachment horizon (1–2.5 m) is universal at the base of the sequence. It is dominated by the sandy material with numerous fragments of mudstones, concretions, and sandy beds. Some inclusions are subjected to plastic deformation. The cement of the sandy mass was previously in a liquefied state, as suggested by its numerous injections into various fractures in both overlying sandstones and large rock fragments.

Thus, the Pui sandstone sections, which are located at a significant distance from each other, contain similar subhorizontal detachment horizons, suggesting that sandstones in the section are allochthonous bodies (Gavrilov, 1992, 2005). This conclusion is also supported by the following fact: the Pui sandstones and the underlying flyschoid sediments differ appreciably in terms of the facies association.

Such a large-scale dislocation of sedimentary masses, one of the largest dislocations in the Greater Caucasus, was obviously triggered by a strong earthquake. The Pui sandstones are exposed near a large fault, which extends over several tens of kilometers along the general Caucasian direction and can be considered a synsedimentary fault. Reactivation of movements along this fault in the early Toarcian initiated a vigorous seismic event, which provoked the detachment and dislocation of huge (kilometer-scale) sedimentary rock slabs along the northern slope of the Early Jurassic paleobasin.

The Lower and Middle Jurassic sections in the northern Caucasus contain many landslides of different sizes and shapes – slabs, blocks, and so on (Gavrilov, 1992, 2005). In most cases, they were created by different-scale seismic events.

CONCLUSIONS

Analysis of the distribution of traces of paleoearthquakes in the Mesozoic–Cenozoic terrigenous sequences of the northern Caucasus revealed that its Alpine epoch evolution, on the whole, was characterized by high seismic activity. At the same time, relatively calm periods were replaced by the reactivation of seismicity often owing to variations in the tectonic setting of the region. This is suggested by signs of the increase of seismic activity confined to the upper part of large sedimentary cycles of the first order: increase in the number of paleoearthquakes preceded and accompanied the transition to the next stage of intensification of the paleobasin bed subsidence.

Comparison of seismites in the different-age terrigenous sequences shows that their manifestation pattern depends appreciably on the composition and lithification degree of sediments. Most favorable for the fixation of traces of earthquakes therein are the sandy–clayey sediments, in particular, Middle Miocene sediments in the eastern Caucasus. The fixation was promoted by the relatively weak cementation of the oligomictic quartz sandstones, prompt liquefaction of the sandy material under the impact of seismic shocks, and high inundation of these beds by elisional waters released from the consolidating organic-rich clays.

Thus, paleoearthquakes promoted the formation of numerous and diverse (in morphology and size) secondary rocks corresponding to a certain seismic event in the sandy–clayey sequence. They make up a single seismic complex including the following elements: seismic event horizons (SEH) represented by intensely deformed and destructurized rocks; associated clastic dikes, sills, and other injection bodies; rocks underlying the SEH and usually retaining the primary bedded structure. These rocks include traces of the seismic impact (sandy beds with signs of liquefaction, abrupt swelling and thinning, horizontal overthrusting, intervals of the destructurized clayey rocks produced by the horizontal shear faulting, jointing, and so on). One can also see fragmentation of beds into blocks, boudinaging, and vertical dislocation of beds relative to each other.

Total thickness of the Middle Miocene seismite horizons in the Buinak Pass section accounts for a significant share in the integral thickness of rocks accumulated during the high seismotectonic activity in the Dagestan sector of the paleobasin and adjacent area.

The pattern of seismites changes toward the west – the Dagestan-type seismites are already missing in the central areas of Chechnya and in Ingushetia due to the attenuation of seismic activity, although lithology of the sequence is usually unaltered. Here, seismic events are suggested by the subvertical pyramidal concretions and carbonate dikes, which were produced by the migration of diagenetic interstitial waters saturated with Fe–Mg–Ca bicarbonates along seismogenic fractures. Further westward, sections in North Ossetia lack explicit signs of paleoearthquakes, probably, owing to variations in the lithology of sediments, in which traces of seismic events are less distinct. Nevertheless, the general trend of east-to-west attenuation of the Middle Miocene seismic activity is recorded quite confidently in the eastern sector of the northern Caucasus. Therefore, we can assume that the modern pattern of seismic activity in the study region already existed here in the Middle Miocene.

In the relatively monotonous clayey sediments of the Khadum Horizon (Oligocene, lower Maikopian), traces of earthquakes are fixed less clearly than in the Chokrakian–Karaganian sequence. In most cases, they are expressed as bed intervals with abundant seismogenic fractures, with morphology depending significantly on the lithification degree of sediments, i.e., thickness of the interval of host sediments. The development of fractures in the near-surface beds stipulated the appearance of cellular structure in sediments. In the deeper and more lithified sediments, fractures were either chaotically distributed or developed along the subvertical direction.

In the clayey sequence of the Khadum Formation, some horizons of fractured rocks display a distortion of the primary horizontal bedding and the development and angular unconformity (~10°) relative to the overlying rocks that lack the jointing. Such association of jointing and intraformational unconformity also could be related to the seismic event. Owing to the abundance of seismogenic jointing, the Maikopian sediments acquired the fissure-type reservoir properties.

The kilometer-scale Lower–Middle Jurassic sedimentary sequence incorporates diverse signs of postsedimentary distortions of the primary sedimentary structure of sediments related to the seismic activity. Often, traces of paleoearthquakes are confined to boundary rocks of different formations related to variations in the tectonic setting (downwarping of the floor) and paleogeographic environment in the paleobasin. We deciphered numerous earthquake-induced downslope dislocations of fragments (sometimes, up to 10–15 km across) of sedimentary sequences in the basin.

In conclusion, let us note that problem of the identification of seismites in sedimentary sequences is not a simple and easy task, because morphologically similar structures are related to the impact of both seismogenic and other processes in some cases.

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