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Geologic constraints on clandestine nuclear testing in South Asia

(arms control/nuclear test ban/India/Pakistan/evasive nuclear testing)

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ABSTRACT Cavity decoupling in salt is the most plausible means by which a nation could conduct clandestine testing of militarily significant nuclear weapons. The conditions under which solution-mined salt can be used for this purpose are quite restrictive. The salt must be thick and reasonably pure. Containment of explosions sets a shallow limit on depth, and cavity stability sets a deep limit. These constraints are met in considerably <1% of the total land area of India and Pakistan. Most of that area is too dry for cavity construction by solution mining; disposal of brine in rivers can be detected easily. Salt domes, the most favorable structures for constructing large cavities, are not present in India and Pakistan. Confidence that they are adhering to the Comprehensive Test Ban Treaty (CTBT) is enhanced by their geological conditions, which are quite favorable to verification, not evasion. Thus, their participation in the CTBT is constrained overwhelmingly by political, not scientific, issues. Confidence in the verification of the CTBT could be enhanced if India and Pakistan permitted stations of the various monitoring technologies that are now widely deployed elsewhere to be operated on their territories.

India conducted its first nuclear test in 1974, at a test site in western Rajasthan near Pokharan. Five nuclear explosions, reportedly of yields ranging from subkiloton to 43 kilotons (kt), were conducted at that site in May 1998. They were followed by a series of Pakistani tests that confirmed the long-suspected nuclear status of that nation. India and Pakistan are now nuclear powers, but the Comprehensive Test Ban Treaty (CTBT) would place strict limits on the development of highly compact and easily delivered multistage thermonuclear weapons and other advanced nuclear weaponry. High-yield thermonuclear weapons cannot be triggered by primaries of just a few kilotons (1), so a verifiable limit of ≈5 kt would place serious constraints on stockpile modernization and maintenance. Therefore, confidence in the monitoring of the test ban would be of considerable value in the Asian subcontinent. Geology and geophysics would play an important role in any attempt to hide a secret testing program and would be central to any monitoring effort directed toward preventing surreptitious testing. We explore conditions in the subcontinent that plausibly might be conducive to evasive testing and show that they are very limited and are relatively easily monitored, given the political will.

Constraints on Clandestine Testing

Non-Geologic Test Scenarios. Many scenarios have been proposed for clandestine nuclear testing, and their drawbacks have been discussed in detail elsewhere (2). For example, concealment by timing a test to coincide with a large earthquake or conducting "ripple" salvo tests is easily thwarted with adequate frequency and azimuthal coverage in seismic data, and ocean-based tests can be detected hydroacoustically. A small test might be "hidden" among mining explosions, but, unless decoupled, it would be limited to very low yields of very limited or no military value. Detecting a test in deep space is far simpler than carrying it out, which is beyond the space flight capabilities of all but a few nations. Tests at or above the surface of the earth leave many telltale geophysical and radioisotopic indicators that allow for detection, as long as monitors remain reasonably diligent.

Cavity Decoupling. Because of the drawbacks of all of these scenarios for clandestine testing, partial or full decoupling of subterranean tests is widely viewed as the only serious threat to monitoring a test ban (3). Decoupling involves conducting a nuclear test so as to reduce the amplitudes of seismic waves to levels below those for a contained, tamped explosion. One less effective way to do this is to conduct the test above the water Table in a large body of dry, porous sediment. Far more effective, in principle, is testing in a large mined underground cavity.

In a tamped underground nuclear explosion, large volumes of rock are exposed to overpressures far beyond the limits of elasticity, causing them to yield and suddenly to be displaced outward a large distance, generating large and easily detected seismic waves. If the explosion takes place within a very large cavity (2–5), however, the pressure of the shock wave in the surrounding rock remains below the elastic limit and produces relatively small displacements. Some early work suggested that, with "full decoupling," seismic amplitudes transmitted into the earth at some frequencies could be reduced by over two orders of magnitude (4, 5). Later studies (2, 3) indicate that decoupling factors of ≈70 may be achieved at low frequencies but decoupling factors at high frequencies are likely to be much smaller. Hence, broadband seismic instruments can be extremely useful in test ban monitoring (6). Joints or other fractures in the surrounding rock may lead to somewhat lower decoupling factors. If the cavity is too small for full decoupling, the seismic waves are reduced by a value smaller than that for full decoupling (7–9).§ The effects of a nonspherical cavity can be quite complicated (10).

Salt has many advantages as a medium for cavity decoupling (3). Salt is not as ubiquitous in the continents as granite, but it is a common rock type that occurs in large and sometimes quite pure deposits. It is ductile yet, under certain conditions, quite strong. Furthermore, its solubility allows the mining of a large cavity without the use of large-scale blasting likely to raise suspicion.

Abbreviations: kt, kiloton(s); CTBT, Comprehensive Test Ban Treaty; Y, yield; SRF, Salt Range Formation.

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Evaporites. Evaporitic rocks can precipitate from a variety of nonmarine waters, but they are most commonly precipitated from seawater. A shallow or constricted sea can produce a gradation in salinity, with a zonation of the type of evaporite minerals deposited, ranging from calcite and dolomite to gypsum and finally halite (NaCl) after a great deal of evaporation. Therefore, these minerals (along with anhydrite, which typically forms by the dehydration of gypsum) are commonly found in association with each other. The abundant evaporite deposits now found in the earth consist mostly of gypsum and anhydrite (both of which are calcium sulfates) and halite, sometimes joined by various potash salts.

Rock salt (halite) has a number of extraordinary geologic, chemical, and engineering properties that cause it to be the focus of concern about decoupled nuclear testing and of this paper. Of these properties, the two most important for the construction of a large cavity are its solubility and ductility. The solubility of salt permits solution mining—dissolving it in water and carrying it away in brine, removing the need for easily detected explosions. The large quantities of water required for solution mining can be obtained from a moderate-sized river, if one passes nearby. The disposal of the brine is more problematic because of the distinct geochemical signal that the brine would leave when mixed with anything but an extremely large amount of water.

At high temperatures, all rocks become ductile. Most common crustal minerals become ductile at midcrustal depths, where temperatures are high enough that intragranular creep mechanisms can accommodate most geologic deformation. Halite undergoes this transition to ductile behavior at exceptionally low temperatures and, therefore, shallow depths. The precise depth depends on the rate of the deformation, the thermal gradient, and the amount of water present, but salt typically becomes ductile within as little as a few hundred meters of the surface and becomes weak within a kilometer or so. This ductility inhibits the formation of fractures and helps to heal those that do occur. The ductility of salt also contributes to diapirism (density driven upward viscous flow), sometimes producing salt domes several kilometers across in areas where a thick salt bed is deeply buried and the overlying sediments are denser. Because the ductility of salt allows it to act as a lubricant for thrust faulting, relatively thick salt also appears in some major thrust faults, and it often fills the cores of anticlines over major overthrusts (11).

Stability of Salt Cavities. Holes in ductile media eventually close. Deeper holes close faster because both overburden stress and the temperature increase with depth, speeding up the creep that leads to hole collapse. Stresses in the material surrounding a spherical cavity are well understood (12), and numerical models can be used to calculate them for nonspherical cavities. In hard brittle rock (such as granite), the concentration of far-field stresses produces a mix of compressional and tensional stresses near the wall of the spherical cavity, but the nearly isotropic far-field stress found in a thick body of salt leads to much simpler stress fields near the walls of the cavity (12). The stress components decay proportionally to the inverse cube of the distance from the center of the hole, so within one cavity radius from the wall, they decay 7/8ths of the way to their far-field values. Thus, the assumption that a body of salt is "thick" is applicable even for a thickness only about twice the hole diameter.

Because of the nature of dislocation creep in halite, the strain rate for salt around a cavity is ≈40× faster (and the cavity life span that many times shorter) than for a cavity at half its depth, even ignoring the important weakening effects of temperature. Therefore, the stability of cavities in salt decreases very rapidly with depth. Filling the cavity with a fluid allows it to be kept open longer, and deeper, than would otherwise be possible, in some cases to depths of 2 km (13). Using water to fill the cavity is likely to be of limited value: salt is far weaker in the presence of water than when dry (14). Furthermore, a decoupled test cannot be carried out in a liquid-filled cavity, so the fluid would need to be removed before a test could be conducted.

The maximum depth for cavity decoupling is controlled by hole stability and depends on a number of factors, including time constraints, the purity of the salt, and the local geothermal gradient, but the practical limit is ≈1 km (Fig. 1). Shallower than a minimum depth, an explosion will not be contained. This depth depends on the details of the local geology, but, for simplicity, we assume that containment is possible deeper than 122 $Y^{1/3}$ m below the surface, a common containment criterion, where Y is the explosive yield in kilotons.

The minimum diameter of the hole required for full decoupling depends on both the explosive yield of the test and the depth at which it is carried out. The Latter criterion for full decoupling (4) states that the volume of the hole is proportional to Y and inversely proportional to the elastic yield stress of the surrounding medium, assuming the yield stress to be proportional to the overburden. This criterion, used in Fig. 1, gives a minimum radius of 25.6 $Y^{1/3}$ m at a depth of 1 km. Thus, even a cavity suitable for full decoupling at 1 kt would be large; that for 5 kt would be large enough to contain the Statue of Liberty and its pedestal (2), or the Taj Mahal. The construction of cavities of those sizes at depths near 1 km would be very expensive, and their use for nuclear testing would be very difficult to do in a clandestine manner in the presence of extensive seismic, satellite, and radioisotopic monitoring.

Alternatives to Salt Cavities. Hard "basement" rock might appear to be the most logical host rock for such a cavity because it is present in many areas, including significant granitic bodies in Pakistan, huge areas of granite in central and southern India, and the basaltic Deccan Traps of western India. A cavity constructed in strong rock can be somewhat smaller than one in weaker rock, because it remains elastic to higher stresses before yielding, but hard rock has many practical drawbacks in cavity decoupling. In particular, such rocks are quite brittle, so, during a long geologic history, with changes in pressure and temperature, they acquire many tensional fractures (joints), typically spaced on a scale of one to a few meters throughout the rock mass. This makes them poorly suited for cavity construction: massive bracing is usually

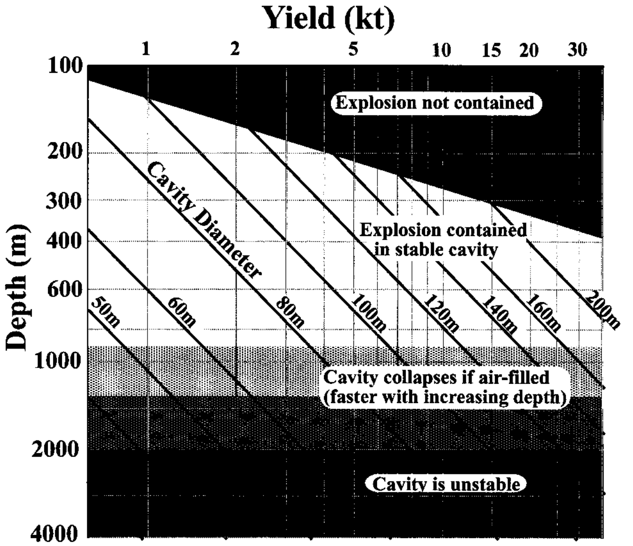

FIG. 1. Stability range for a cavity in salt. Depth range (logarithmic scale) is bounded at shallow end by need for containment and at deep end by the need to keep cavity open long enough to permit decoupled nuclear testing. Diagonal lines indicate minimum cavity diameters required for full decoupling.

required to keep a large cavity open (15). Large shallow cavities and small (or tunnel-like) deep cavities have been built in hard rock. Little engineering experience exists, however, for the construction and maintenance of roughly spherical deep holes that are large enough for full decoupling of even a relatively small nuclear test. Furthermore, the quantity of required blasting and the need to remove huge quantities of excavated rock make secrecy exceedingly unlikely. The fractures make containment of radionuclide-bearing gases difficult to predict, and, unless it is very deep, a cavity used for a test is likely to collapse and may create an easily visible crater at the surface. Thus, cavity decoupling of military significance in hard rock, although plausible, would be exceedingly expensive and difficult, if not impossible, to do in secret.

Testing can also be conducted in dry alluvium, which is a geologically young sediment of low rigidity. An explosion in dry alluvium produces relatively small seismic waves because much of the energy that would otherwise produce seismic waves goes into closing of air-filled pore spaces, reducing the body waves about one magnitude unit. One portion of the Nevada Test Site is among the few regions in the world with areas of thick alluvium and a climate dry enough to allow the water table to be very deep. Most areas with thick alluvial deposits are fairly wet, at least seasonally, so the water Table is generally fairly shallow and the dry alluvium is generally too thin to assure containment of a test. In deserts in which the water table is deep, including the Thar (or Great Indian) Desert (Fig. 2), the surficial sand and porous alluvium is generally too thin for containment of any but the smallest tests. It is, however, interesting to note that two announced Indian nuclear explosions on May 13, 1998 reportedly were conducted within a sand dune in the Thar Desert. It is not clear whether these very small tests, which according to the Indian government had yields of 0.5 and 0.3 kt, had a significant radioactive release at the surface because data from radioisotopic monitoring stations are not yet publicly available from the region. Estimates of the combined yields of these tests (16), using the nearby Nilore Pakistan seismic station, are <0.3 kt (300 tons), assuming they were conducted in dry alluvium. Baluchistan in southwestern Pakistan is the one area in either India or Pakistan with locally thick young sediment and a dry climate where the water table might be reasonably deep.

Testing at a relatively shallow depth exacerbates a problem characteristic of testing in alluvium—the venting of radionuclides—and increases the likelihood of detection of the test by treaty monitors. Significant venting has occurred after some U.S. tests in alluvium in Nevada (6). An inexperienced nuclear power seeking to test secretly in dry alluvium would have to accept a particularly high risk of venting and its detection, so the risk of detection hardly seems worth the limited benefit. Therefore, the most plausible means of reducing the seismic signal from a nuclear test to evade detection remains conducting it in a large underground cavity in salt.

Evaporites in Pakistan: Possibilities for Decoupled Testing

Eocambrian Salt (Salt Range). The minor deposits of gypsum and anhydrite in Pakistan (17, 18) are not suitable for solution mining and cavity decoupling, but two important deposits of rock salt need to be considered in detail: the Eocambrian age Salt Range Formation (SRF) and the Bahadur Khel Salt.

More than 500,000 tons of salt is mined each year from the SRF of northern Punjab, all from a few mines in a small geographic area where it occurs near the surface. As the horizon for thrust detachment in that area of the Himalayan foreland, the SRF is the lowest formation exposed in the Salt Range, where it includes large lenses of pure halite, along with many other rock types. Near Khewra, its lowest member is interbedded with seams of "red earthy salt" totaling ≈90 m (17). Another less pure bed ≈75 m thick occurs above it, as do other evaporites (19). The original depositional thickness of the SRF was ≈1,000 m (20), but it is tectonically thickened within the Salt Range thrust and locally exceeds 2 km (21, 22).

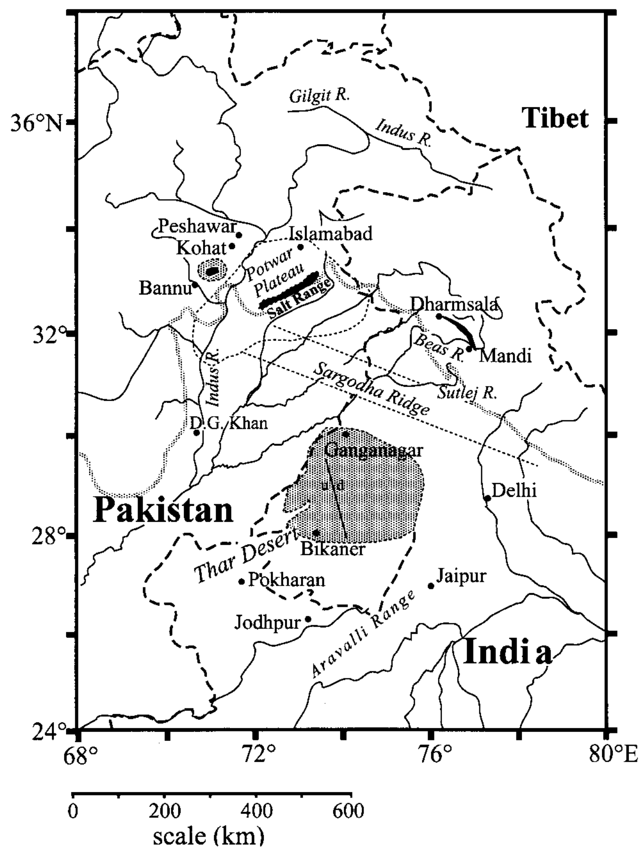

FIG. 2. Areas with salt deposits in northern Pakistan and India relevant to cavity decoupling. Dotted lines indicate international borders. Dashed band shows approximate location of basement high of Sargodha Ridge, shaded curve indicates frontal extent of Himalayan deformation, and "u" and "d" indicate the upthrown and downdropped sides, respectively, of large normal fault in That Desert. Small dark areas in Salt Range, near Bannu in northern Pakistan, and near Mandi in northern India are regions of easily accessible salt. Irregularly shaped shaded areas near Bikaner and Bannu are regions of less accessible salt.

The SRF extends over 100 km beneath the central Potwar Plateau and the Salt Range. In most of the area beneath the Potwar Plateau, the SRF is several kilometers deep, far too deep for a stable cavity. In the central and western parts of the Salt Range, a major ramp thrust (the Salt Range Thrust) has propagated over a large flexural normal fault (Fig. 3*a*) that offsets both basement and the SRF (21, 23). Beneath the eastern part of the Potwar Plateau, the SRF is relatively thin and is generally 4 km or more below the surface. It is ≈2 km deep in some anticlines (Fig. 3*b*), and it approaches the surface at the Domeli thrust (24).

Much of the stratigraphy appears to be continuous across the basement high of the Sargodha Ridge (Fig. 2), and the SRF remains thick far to the south of the ridge. The ridge appears to be at or near the southern limit of substantial halite in Pakistan. A 900-m-thick sequence of SRF that has been drilled 280 km south of the Salt Range (22) includes no salt (18, 25) and is too deep for a stable open cavity even if salt were present.

In most of the central Salt Range, the Jhelum river is located 10–15 km south of the deformation front. With a flow of $\approx 3 \cdot 10^{10}$ m^3 per year at the Mangla reservoir (18), the Jhelum is a highly seasonal but substantial river. The geochemical

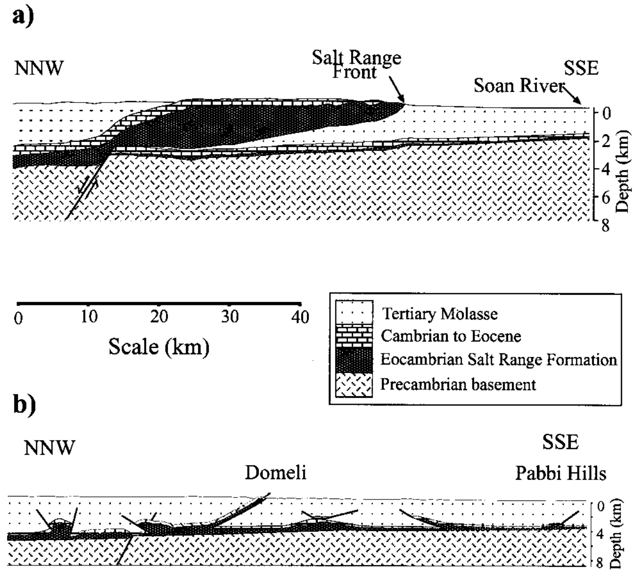

FIG. 3. (*a*) Cross-section of Himalayan deformational front showing distribution of Salt Range Formation along frontal Salt Range Thrust (21), with 2× vertical exaggeration. (*b*) Cross-section of the eastern Potwar Plateau, southeast of Islamabad (24). Substantial salt beneath the basin is almost entirely too deep to be of use in cavity decoupling. No vertical exaggeration.

signal in the river from the erosion of halite could not conceal the salinity associated with the disposal of brine from the construction of a large cavity, unless the disposal occurred over a period of at least several years. The substantial distance between the river and the likely area of cavity construction (Fig. 3*a*), as well as the large quantities of salt brine requiring disposal, would nonetheless make this disposal extremely difficult to conceal.

The Eocambrian salt extends at least some distance to the west of the Salt Range, and it is closely involved in overthrusting in the Kohat Plateau and the Surghar Range (26). In the Surghar Range, the SRF reaches within 4 km of the surface, but nowhere west of the Salt Range is it shallow enough to be useful for the construction of a stable cavity.

Eocene Salt (Kohat Region). Although the SRF may not extend northwest into the Kohat region, much younger salt is found there. The Bahadur Khel Salt of Early Eocene age (Fig. 2) is of only limited geographic extent (18, 20, 27). Where the salt is at or near the surface, it is thinner than 100 m thick, but it is locally much thicker in the subsurface (27): the true stratigraphic thickness at the Bahadur salt quarry is estimated to be ≈300 m (17).

A series of folds and thrusts bring the salt to the surface in isolated patches throughout a 10- × 40-km area just north of Karak (27). It is probably brought near the surface and is locally suitable for cavity construction in an area about twice that length and width to the east of Bannu (Fig. 2). The Indus river in northern Pakistan has a net flow substantially larger than that of the Jhelum river, averaging $>10^{11}$ m^3 per year (18). Nonetheless, given a natural chlorine ion concentration of ≈7 milligrams per liter in the northern Indus (28), the disposal of salt removed from a 60-m radius cavity, one suitable for full decoupling of ≈10 kt, would more than double that concentration for two years. Furthermore, although the Indus River passes ≈30 km to the east, no large river runs directly past areas in which the salt is accessible. In combination, these factors would make the surreptitious disposal of so much brine unlikely. Because the thickness of the Bahadur Khel Salt is uncertain, the part of the Kohat Plateau where it is likely to be accessible, perhaps 1,500 km^2 in area, requires monitoring for potential covert testing.

Evaporites in India: Possibilities for Decoupled Testing

For such a large country, India has very few accessible deposits of evaporites. Active rock salt mining in India is limited to the late Precambrian Shali formation at Drang and Guma, in the Mandi district of the northern state of Himachal Pradesh (29). This yields ≈4,300 tons of salt per year, two orders of magnitude less than production in the northern Punjab of Pakistan. The only other large salt deposit in India is the Nagaur–Ganganagar evaporite basin beneath the Thar Desert (Fig. 2), which does not approach the surface and is not mined.

Precambrian Salt (Himachal Pradesh). The Shali formation is a thick sequence of mostly carbonate rocks that includes some salt (29). Throughout the Mandi area, it is imbricated and bounded on both sides by thrusts (30, 31). The purity of the salt is variable, ranging from ≈70–90% NaCl (29, 34).

The salt beds are always proximate to and on the Himalayan (hanging wall) side of the large thrust fault (35). They are exposed at a string of localities along ≈70 km of the Mandi thrust (31). Estimates of the total length over which the salt appears, based in part on the distribution of the associated "Lokhan" marly sequence (32), range from 100 to 180 km. Drilling produced salt or salt grit ranging from 13 to 135 m thick (33), which probably is not a maximum. Thus, the thickness and purity of the salt are likely to be at least minimally adequate for cavity decoupling.

Near Megal and Drang, the Megal thrust is a structural flat (30), essentially parallel to the 45° dip of the sedimentary rocks of the mid-Miocene Kasauli formation beneath the thrust (Fig. 4). As a result, the salt rapidly deepens with distance from the thrust front. Combined with the sharp topographic relief in the hanging wall of the Mandi thrust, this indicates that, within 2 km from the thrust front, the Mandi salt is likely to be too deep to be usable for the construction of large, stable cavities. Hence, the area within which cavity construction is possible

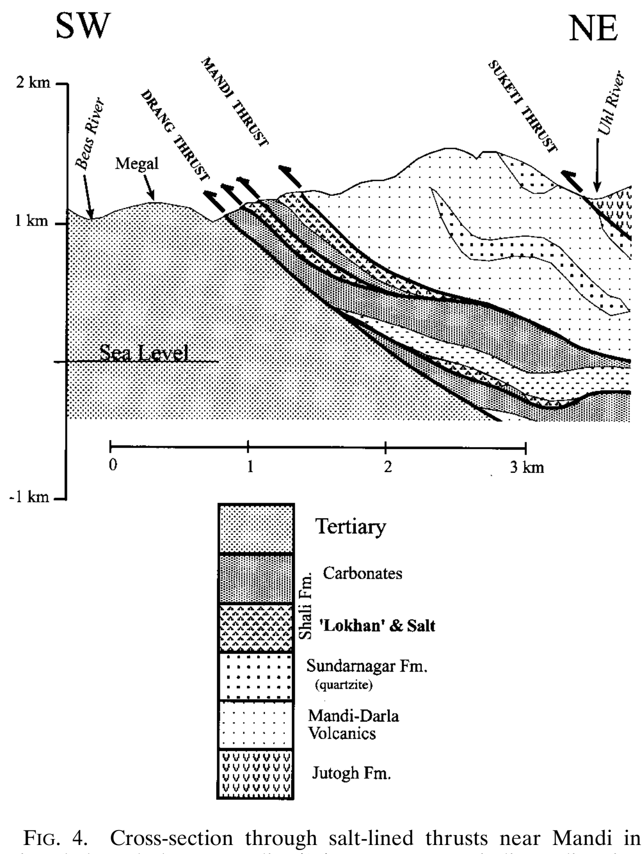

FIG. 4. Cross-section through salt-lined thrusts near Mandi in Himachal Pradesh state, India. (37). Heavy arrows indicate direction of thrust motion along Himalayan foldbelt.

constitutes a very narrow strip as much as 200 km long but probably only 2–3 km wide.

The supply of water for solution mining appears to be adequate, with several rivers running through the area (Fig. 2). Furthermore, this is one of the wetter areas of India: in a narrow band along the Himalayan front, annual precipitation exceeds 4 m. Runoff is channeled down the enormous topographic relief along the Mandi thrust front through many streams and into the Satluj and Beas rivers. Roughly 60% of the flow occurs during the monsoon season (June-August), and most of the rest is runoff from the spring thaw in the Himalayas (18), so the spring and summer months are the most favorable for the clandestine construction of a large cavity by solution mining. Dissolving the salt from a 60-m radius cavity in the annual flow of the Beas river past the Mandi Plain would produce a salinity of $\approx 10^{-4}$. This would constitute an unmistakable geochemical signal, increasing the chlorine ion concentration by >60 milligrams per liter, to a level an order of magnitude greater than that typical for Asian rivers (28). The water supply is adequate for solution mining of a large cavity, but, if the brine were drained into the Beas (or any other river) within a period of a few years or less, the chemical evidence for such activity would be evident from simple downstream water sampling.

Eocambrian Salt (Western Rajasthan). The Nagaur–Ganganagar evaporite basin lies beneath ≈50,000 km^2 of the Thar (Great Indian) desert in western Rajasthan, west of the Aravalli range (36, 37). This basin extends in a 200-km-wide band from Jodhpur, northward across the border into Pakistani Punjab (Fig. 2). The northern part of the basin includes the Hanseran Evaporite Group, with 100–650 m of diverse rocks, including dolomite and evaporites, interstratified along with claystones (37, 38).

Evaporites are not exposed at the surface, and below the surface they appear to be limited to north of ≈28°N, near Bikaner (Fig. 2). The evaporitic, halite-bearing rocks thin eastward and apparently terminate along the N-S striking Sardarsahar Fault, a (west down) normal fault (Fig. 5). The top of the halite horizon deepens westward, from ≈275 m below the surface near the middle of the basin to >1,000 m near Pugal in the west (37). These evaporites and the Salt Range Formation of Pakistan may be part of the same large depositional basin, but the two centers of evaporitic deposition probably are now isolated from one another.

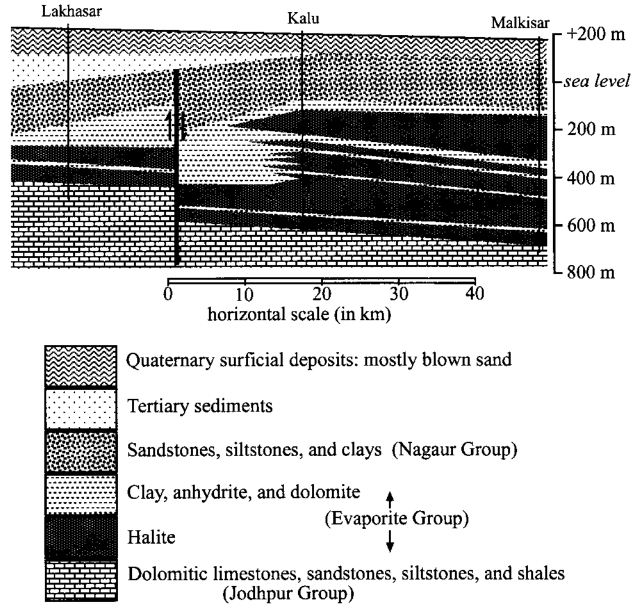

FIG. 5. East-west cross-section in Thar Desert near 28.5°N (≈50 km north of Bikaner), showing the evaporites of the Ganganagar-Nagaur basin (36, 37). Note large (30×) vertical exaggeration.

In the western part of the Nagaur–Ganganagar evaporite basin, where the salt is >1 km deep, ductile creep would limit the likely stability of a large cavity. There is, however, a broad region in which the salt is shallower. In an area ≈100 km wide, from near Bikaner in the south to near Ganganagar in the north (and thence across the border), the salt appears to be at appropriate depths of a few to several hundred meters. Within that region, the pertinent issues for cavity decoupling are the thickness and purity of the salt, the prospects for concealing the process of solution mining, and background seismicity. The purity and thickness of the salt horizons vary considerably within the basin (38), but there may well be extensive regions in which salt thickness and depth are adequate for cavity construction. Nevertheless, the prospects for concealment in this region are extremely poor, as the Thar Desert lacks any substantial water supply for solution mining and there is no obvious place to dispose of large quantities of brine. Significant mining activity that could serve as a cover for surreptitious solution mining is lacking. Furthermore, the background seismicity in the area is low, so that seismic activity of any kind, including that from a decoupled test, would attract attention. In summary, despite the large quantities of salt that it contains, the Nagaur–Ganganagar evaporite basin is an easily monitored threat for cavity construction and clandestine testing.

Conclusions

Only two areas in India and two in Pakistan have reasonably thick salt at depths appropriate for the construction of a large and reasonably stable cavity. An ≈20,000-km^2 region of the Thar Desert in western India is, geographically, the largest area of concern, but the barren, arid nature of this region would aid enormously in monitoring efforts. Conditions are somewhat more favorable for cavity construction in a small area along the Himalayan front near Mandi in the state of Himachal Pradesh. Its salt, however, is at best marginal in thickness and is located in a very narrow thrust-controlled strip. Pakistan also has only two important areas of special interest for cavity decoupling. The Salt Range Thrust brings a salt-bearing formation within ≈1 km of the surface in a 5,000-km^2 area just north of the Himalayan deformation front. Salt mining in that area might provide a useful cover for evasive testing. The Bahadur Khel Salt is brought near the surface by anticlines in the 1,500-km^2 area of the Kohat Plateau. Despite physical and geochemical difficulties associated with trying to keep cavity construction secret, this area provides a high quality salt that may locally be thick enough and at appropriate depths for such construction.

So far, India or Pakistan have gone to great lengths to publicize their nuclear tests and probably to exaggerate their yields (16). Unless they were to resort to decoupling in dry alluvium or hard rock, each of which has its own very serious drawbacks, secret testing of military value would have to be attempted in very large cavities in salt. That would limit the effort to the above four areas, which total ≈27,000 km^2. Hence, the ability of India and Pakistan each to have confidence that the other is adhering to a CTBT is enhanced by their geological conditions, which are quite favorable to verification, not evasion.

The existing seismic stations of the International Monitoring System for the CTBT provide coverage for India and Pakistan down to magnitudes, m_b, <4.0: i.e., for tamped explosions of $Y \geq 1$ kt. The Soviet partially decoupled explosion of 8–10 kt in 1976, which was detonated in a huge cavity in salt created by a tamped nuclear explosion of 64 kt, was of $m_b = 4.07$ and was recorded by many stations. Availability of data from the six seismic stations in India and Pakistan stipulated in the Protocol Annex to the CTBT should provide an identification threshold for fully decoupled explosions of $Y \geq 3$ kt. Isotopic monitoring stipulated in that Annex as well as satellite imagery would provide additional constraints on evasive testing.

The distribution of salt may present a wider range of options for the construction of a large cavity in some other nations, including Iran. In India and Pakistan, however, geologic factors favor monitoring. Therefore, their participation in the CTBT is constrained by political, not scientific, issues. Confidence in the verification of the CTBT would be enhanced if they permitted stations of the International Monitoring System to be operated on their territories. Other significant confidence-building measures could include preannouncement of large chemical explosions, water sampling to detect salt concentration in rivers, and the exchange of geological and geophysical data.

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